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SCIENCE FOR A SUSTAINABLE DEVELOPMENT

SUSTAINABILITY, FINANCIAL AND QUALITY EVALUATION OF DWELLING TYPES

SUFIQUAD

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FINAL REPORT

SUSTAINABILITY, FINANCIAL AND QUALITY EVALUATION OF DWELLING TYPES "SUFIQUAD"

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SUMMARY

A. Context

Current approaches in Belgium aiming at a sustainable development of the building sector focus on different aspects separately (e.g. building materials, energy use, transport), while abstracting the complex interrelations. This allows for a detailed analysis but misses a global objective by losing the overall picture. Since the design of a building (amongst others typology, lay-out, dimensions, orientation and location) determines the overall environmental impact, a building cannot be equated to the sum of its constituting components. However, a life cycle assessment of a building to date is most often carried out at the level of materials or components. Moreover, financial decisions are to date most often exclusively based on investment costs not considering the life cycle consequences. An evaluation tool based on representative environmental and financial data for the Belgian context which enables such a comprehensive life cycle assessment is therefore required.

The originality of the integrated approach of this research lies in the fact that the analysis is carried out at the building level, considering all interrelated influences and stakeholders. All aspects of interest are considered by integrating financial evaluation techniques (i.e. investment cost evaluation and life cycle cost analysis (LCC)), environmental evaluation methods (i.e. LCA and environmental external costs) and performance evaluation (multi-criteria analysis (MCA)).

B. Objectives

The project departed from the need for an integrated approach to search for actions in order of priority to reduce the environmental impact of the building and housing sector, taking into account building performances and financial consequences. The aim was to develop a methodology and tool to evaluate both the initial and future costs (financial and environmental external) and benefits (qualities) of different housing types. Through the investigation of a number of technical, spatial and user behaviour parameters recommendations for the stakeholders and a basis for policy making were aimed at.

More particularly, the goal was to clarify possible conflicts between decisions based on financial investment costs, life cycle financial costs, environmental investment costs, life cycle environmental costs, the sum of both and finally these costs in relation to the performance of the dwellings. A background document for policy making which considers policy measures to move towards a more sustainable building and housing sector was the final objective.

C. Conclusions

An important outcome of the research is an **integrated assessment method and tool** for the evaluation of life cycle environmental external costs, financial costs and qualities of buildings (or building parts), based on data representative for Belgium. The tool allows the identification of priority of actions to efficiently move towards a more sustainable dwelling stock. Thanks to the flexibility and transparency of the tool, future adjustments based on new insights concerning environmental indicators, monetary values, scenarios (transport, end-of-life, cleaning, maintenance, and replacement frequencies) are possible, as well as expansion for new innovative materials, products and techniques.

Several aspects were investigated through the **implementation** of the developed assessment tool. It concerns the analysis of building elements (e.g. outer and inner walls, flat and pitched roof, and floor on grade), the analysis of representative newly built dwellings, the analysis of renovation measures and how they compare with further use of the non-refurbished dwelling and new construction, as well as the evaluation of current policy measures related to sustainability of dwellings. The most important findings for each of these implementations are summarised in the subsequent paragraphs.

The **analysis of the building elements** considered 'all' current available materials, products and techniques for which the necessary environmental and cost data were available. Valuable information is retrieved as outcome for designers and building owners providing a comparison of the initial and life cycle (financial, environmental and total) costs of most currently available technical solutions for each building element. Moreover, for each element of the building envelope, the optimal insulation thickness for the different considered insulation materials was determined and can be used in building practice.

In general, it can be concluded that the current insulation requirements of the energy performance standard are too low compared to the life cycle financial and environmental optima. Beside the insulation level, the finishing was identified as important parameter for the life cycle environmental external cost (often more determinant than the building structure). Both the production process and the service life (and thus replacement rate) of the materials were identified as important aspects for the life cycle environmental external cost of materials. Wood and wood-based products led to unexpectedly high environmental costs due to land use. As the uncertainty of the external cost of land use is high, further research is recommended.

The search for the priority of actions for reducing the life cycle environmental, financial and total (sum of both) cost was based on the **analysis of 16 representative newly built dwellings**. The most important conclusions to move towards a more sustainable dwelling stock were the following.

For an efficient reduction in life cycle external cost, the location, choice of building characteristics (e.g. size of the dwelling, thermal compactness, glazed area and orientation), insulation level, air-tightness and choice of technical systems were proved to be the order of priority. For the insulation level one should focus on the complete building skin, striving for the optimal insulation thicknesses as defined based on the assessment at the element level. For a limited budget, actions in order of priority should be defined. These depend on the efficiency of the cost reduction of each element, the ratios of the elements and the available budget. In addition, it is important to take into account the (im)possibility of improvements later on in the life cycle at reasonable costs (e.g. floor insulation).

Both the priorities and optima based on financial and environmental external costs differ. Indeed, from an environmental perspective the dwellings should be insulated better than would be done solely based on financial costs. However, energy-reduction measures based on life cycle financial costs proved to result in lower life cycle environmental costs than those solely based on financial investment costs. An integrated assessment of each measure remains however required because not all measures based on life cycle financial costs are in line with those based on life cycle environmental costs (e.g. Asian bluestone is cheaper but has a higher environmental external cost than Belgian bluestone).

The environmental optimisation based on energy-related measures resulted for ten of the sixteen analysed dwellings in a reduction in the life cycle financial cost. The majority of these measures were thus justifiable from a financial life cycle cost perspective. Despite this observation, it is important to evaluate all measures carefully because some of the environmental optima resulted in an increase in the life cycle financial cost. The affordability of the environmental optima of the energy-related measures was positively confirmed by observing an average increase of financial investment cost of only 6%. If this is not affordable for the private dwelling owner, it should be through means of support from the government or third party private investments. No straightforward conclusions could be drawn for the non-energy related measures (e.g. material choice). Each single measure therefore requires an assessment based on financial and environmental cost.

Because the environmental external costs were relatively small compared to the financial costs, internalisation of these external costs did not influence the final decisions to a great extent but neither led to unaffordable housing. It is therefore advisable to analyse financial and environmental external costs separately too.

The majority of the optimal dwellings (both based on financial and environmental external costs) proved to be characterised by a yearly net heating demand higher than the low-energy (30 kWh/m² floor) and passive standard (15 kWh/m² floor). However, the low-energy or passive standard may be the optimum for dwellings with an adapted design, layout, glazing area and orientation (which was not investigated in this research). Nevertheless, based on the research results an adaptation of current building practice and layout prescriptions is clearly required to develop low-energy and passive houses in an efficient way.

The inclusion of the quality evaluation confirmed the presumption that dwellings with a higher cost (financial and/or environmental) may be preferred because of their higher quality. This is not experienced as problematic, as long as the dwelling owner/renter is willing to pay for the extra costs (financial and environmental). Moreover, it is obvious that quality is subjective and thus that a certain dwelling is differently appreciated by different persons or at different moments during one's lifetime. An increasing number of singles, an ageing population and a multi-cultural society indicate a strong need for a diversified dwelling stock in Belgium. A mix of high-quality small houses/apartments and large dwellings with a higher degree of flexibility seems to be an important feature of sustainable housing

The **analysis of renovation measures** was based on two case studies from a different construction period and focused on energy-reducing measures. The order of priority of the measures differed for the two case studies (terraced dwelling, built before 1945 and a detached dwelling built between 1971 and 1990). Renovation of both dwellings resulted in lower life cycle environmental external costs. The measures were however most effective for the oldest dwelling because of its lower initial insulation value and older technical services. From a financial point of view, the considered renovation measures were only of interest for the oldest dwelling.

The **comparison between further use of the non-refurbished dwellings, renovation or new construction** revealed that for the oldest dwelling (built before 1945) further use of the dwelling without refurbishment leads to the highest and renovation to the lowest life cycle costs. The same was true for the more recent dwelling (built between 1971 and 1990) based on environmental costs, but from a financial point of view, further use of the non-refurbished dwelling led in this case to the lowest life cycle cost. However this final conclusion was only true when a remaining service life of 60 years was considered.

For a prolonged service life of 120 years, most renovation cases became financially more interesting than the further use of the non-refurbished dwelling.

To date the government invests greatly in energy efficiency measures through tax reduction, green energy certificates and regional and local grants. The **evaluation of current financial incentives** regarding photovoltaic panels and roof insulation, proved that (the order of magnitude of) these are not always justified (e.g. some measures are already financially interesting without subsidies or subsidies exceed the savings in environmental external costs). Each policy incentive should be carefully considered and be based on the analysis of both financial and environmental lifecycle costs.

D. Contribution of the project in a context of scientific support to a sustainable development policy

The SuFiQuaD model balances the environmental and economic dimension of sustainable development for dwellings in the Belgian context. It allows quantified evaluation of myriads of building solutions both from the private "self interest" perspective as well as the societal environmental perspective. It thus allows determining the priority of actions for a more sustainable Belgian dwelling stock, the financial consequence of these actions and therefore also the size of justifiable financial incentives from an environmental policy point of view.

Keywords: building element, dwelling stock, environmental external costs, life cycle assessment, life cycle costing, optimisation, policy, quality assessment, sustainability

1. INTRODUCTION

a. Context

Current approaches aiming at a sustainable development of the building sector are focussing on the different actors separately (e.g. building materials, energy use, transport), while abstracting the complex interrelations. This allows for a detailed analysis but misses a global objective by losing the overall picture. Worth mentioning in this perspective are 'the Energy Performance Standard (EPB)' (a.a. 2005a) and the 'Best Available Techniques (BAT)' - studies at sector level (emis 2009).

Life Cycle Assessment (LCA) in the building sector is most often carried out at the level of materials and components and not at the level of the building. This is summarized in the document: 'Life-cycle assessment in building and construction: a state-of-the-art report' (SETAC 2003). Since the design of a building (amongst others typology, lay-out, dimensions, orientation and location) determines the overall environmental impact, a building cannot be equated to the sum of its constituting components.

The originality of the proposed 'integrated' research lies in the fact that the analysis is carried out at the building level, considering all interrelated influences and stakeholders. All aspects of interest are considered by integrating financial evaluation techniques (i.e. investment cost evaluation and lifecycle cost analysis (LCC)), environmental evaluation methods (i.e. LCA and environmental external costs) and performance evaluation (multi-criteria analysis (MCA)).

b. Objectives

The project departed from the need for an integrated approach to search for actions in order of priority to reduce the environmental impact of the building and housing sector, taking into account building performances and financial consequences.

The aim was to develop and apply a methodology to evaluate both the initial and future costs (financial and environmental external) and benefits (qualities) of different housing types. Through the investigation of a number of technical, spatial and user behaviour parameters recommendations for the stakeholders and a basis for policy making were aimed at.

More particularly, the goal was to clarify possible conflicts between decisions based on financial investment costs, lifecycle financial costs, environmental investment costs, lifecycle environmental costs, the sum of both and finally these costs in relation to the performance of the dwellings.

A background document for policy making which considers policy measures to move towards a more sustainable building and housing sector was the final objective.

2. METHODOLOGY

a. Research approach

In FIGURE 1 the research approach is shown schematically. During the first research phase, the methodology and assessment tool were developed, the necessary data were gathered and several selected extreme cases were analysed. Based on the implementation experience and results, both the method and tool were refined. The improved version of the assessment tool was in the second phase applied to several representative cases. Based on this second implementation, the method and assessment tool were again revised and future further improvements were suggested. In the final stage of the research, policy recommendations were formulated based on the developed methodology and results of the implementation. Moreover, the tool was used to evaluate current policy measures.

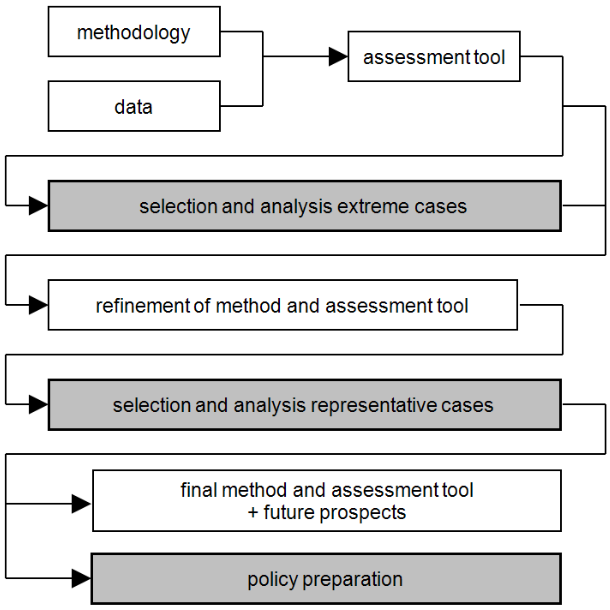


FIGURE 1 Research approach

b. Integrated lifecycle assessment

Several analytical methods were combined to overcome the limits of each single method and to develop an integrated lifecycle approach. A quantitative lifecycle approach was followed to ensure the necessary transparency and reproducibility of the results. Three methods (LCA for environmental impacts, LCC for costs and MCA for the performance evaluation) were integrated through a Pareto optimisation procedure. In order to manage the complexity and enable the assessment during the different phases of the design process, the element method for cost control was used and extended to lifecycle costs and environmental impact.

The lifecycle of the building includes the initial phase (production of the materials, transport to the construction site and construction processes), the use phase (cleaning, maintenance, replacements) and end-of-life (EOL) phase (demolition, transport to sorting and EOL treatment plants, EOL treatment). The life span of the building was assumed 60 years with a sensitivity of 30 and 120 years. The number of replacements of the building parts is determined by the service lives of the latter and is based on an extended literature study (BCIS 2006, Perret 1995, BRE 2000, IVAM 1995, Blom 2005, SBR 1998, ABSW 2006, Haas et al. 2006a-b and ELEA 2007).

The detailed study of the energy consumption was limited to space heating, domestic hot water production and ventilation and was estimated based on the Flemish implementation of the Energy Performance of Buildings Directive (EPBD) (a.a. 2005a). Since the EPBD was developed for comparative analysis rather than for estimation of real energy use, some adaptations were made. The energy use for the production of domestic hot water was based on the PHPP approach (Feist et al. 2001-2006), boiler efficiencies were calculated based on the Energy Performance Certificate (EPC) formulae and on the formulae derived by Van der Veken and Hens (2010) and the rebound effect was considered based on the formulae derived by Hens et al. (2010). Moreover, it was assumed that the dwellings were not actively cooled but that overheating problems were solved by shading devices and/or increased ventilation rates. The solar gains were moreover remodelled since it was proved that the EPB software programme wrongly calculates these. In addition, the electricity use for appliances and lighting, water consumption during use phase and transport of the inhabitants were roughly estimated to investigate their importance in relation to the other phases and processes.

c. Environmental impact assessment

For the assessment of the environmental impacts, several methods are available (Finnveden and Moberg 2005). LCA was found the most suitable method for the purpose of this research and has a broad international acceptance. According to the ISO 14040 standard, LCA is defined as *"the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its lifecycle"* (2006a, p. 2). Although LCA – in current practice – covers a great part of the total environmental impact, it does show some limitations which should be kept in mind when interpreting the results. These limitations concern the restriction to regional and global impacts to the external environment (e.g. local effects to manufacturers or indoor air quality in dwellings are disregarded) and the exclusion of effects with a low plausibility of occurrence (e.g. risks of nuclear waste).

The LCA procedure is defined by ISO 14040 (2006a) in four iterative steps (goal and scope definition, lifecycle inventory, lifecycle impact assessment and interpretation of the results).

Because of the complexity of buildings and their typically relative long life span, applying LCA to a building is more than the addition of building materials and has become a distinct working area within LCA practice (IEA 2004, SETAC 2003, Ortiz et al. 2009). A comparison of 25 recent (2000 – 2007) assessments within the building sector by Ortiz et al. (2009) revealed that these differ in the environmental loads considered and the functional unit chosen. Moreover, a large number of LCA studies deal with a specific part of the building lifecycle but few of them deal with the whole life span.

The non-transparency of the available LCA tools for buildings led to the need for the development of a specific tool within this research. This was also required because of the too limited flexibility of the existing tools to enable investigation of the research questions. The most important assessment options within this research are elaborated in the subsequent paragraphs.

The lifecycle inventory was mainly based on the Swiss ecoinvent database version v2.1 (Ecoinvent 2009), adapted for the Belgian context. Furthermore the modelling of import of materials (i.e. blue stone from Asia and wood from different origins, passenger transport, recycling processes and CO_2 emissions (and uptake) of wood products were refined and further developed for the purpose of this research. Transport and EOL scenarios of the building materials were defined based on a limited survey. The initial impacts were limited to the material production and material transport processes, while transport of the building workers and the construction processes were not considered due to lacking data. Both the environmental benefits and the impacts related to the end-of-life (EOL) treatment are allocated to the analysed building. (Allacker 2010)

The selected hybrid method is an endpoint approach, expressing the impacts in a single monetary value to enable straightforward decisions and improve comprehension. It considers as many impacts as possible – based on Eco-Indicator99 (Goedkoop and Spriensma 2001) - in order to make a comprehensive assessment.

Based on an extensive and in-depth literature review, it was decided to combine several existing methods to determine the monetary values based on the willingness-to-pay approach. These costs are referred to as environmental external costs (European Commission 2008, Mizsey et al. 2009) and occur when the social or economic activities of one group of people (or of an individual) have an impact on another or on the whole society, and when the first group fails to fully account for these impacts (European Commission 2008).

These costs are most often passed on to the society as a whole or to future generations. The considered emissions and impacts in combination with the assumed monetary value and sources (used for the determination of the monetary values) are summarised in TABLE I.

TABLE I Overview of the key data for the monetary valuation of the impacts (based on Spirinckx et al. 2008, 43 and Allacker 2010, 69)

Emissions or impact	**external cost**	**unit**	**source**
Air borne emissions			
PM2,5	61.000	€ /ton	(1)
SO_2	11.000	€ /ton	(1)
NO_x	5.200	€ /ton	(1)
NH_3	30.000	€ /ton	(1)
VOC	2.500	€ /ton	(1)
greenhouse gasses: CO_2 equivalents			
low estimate (a)	19	€ /ton CO_2 eq.	(2)
mid estimate (b)	50	€ /ton CO_2 eq.	(3)
high estimate (c)	150	€ /ton CO_2 eq.	(4)
impacts assessed by Eco-Indicator			
human health	60.000	€ /DALY	(5)
quality of ecosystems	0,49	€ /PDFxm²xyear	(6)
depletion of resources	0,0065	€ /MJ	(7)
fresh water	1,22	€ /m³	(8)

Notes and sources: (a) Low estimate, to be used for sensitivity analysis
(b) Mid estimate
(c) High estimate, to be used for sensitivity analysis
(1) ExternE – CAFE project (Holland et al. 2005, 13-17), mid estimate, data for Belgium
(2) ExternE (European Commission 2008)
(3) (Davidson et al. 2002)
(4) (Watkiss et al. 2005)
(5) ExternE (European Commission 2008) and Torfs et al. (2005)
(6) Restoration cost (Ott et al. 2006)
(7) WETO-H2 (European Commission 2006)
(8) (De Nocker et al. 2007)

d. Financial evaluation

The financial evaluation consists of two aspects: the initial cost is evaluated in terms of affordability and the lifecycle cost in terms of life time efficiency. Even though some measures may lead to a reduction in environmental impact, the above criteria are of primary importance for the average Belgian citizen to conduct a certain measure. The lifecycle costs were calculated through the sum of the present values of all costs occurring during the lifecycle of the dwelling (Flanagan et al. 1989, ISO 2006b). Several sources were consulted to gather the necessary cost data.

The initial construction costs were mainly taken from the ASPEN (2008a) database, combined with material specific data if required. The construction cost includes the material, labour and indirect costs. The energy costs were estimated based on average prices for households in Belgium in 2008 (European Commission 2009).

The EOL costs were based on a limited survey, conducted in 2009 by CSTC. The cleaning and maintenance costs were retrieved from literature (Pasman et al. 1/1993, Hollander den et al. 3/1993, Ten Hagen Stam 2000a-b-c, ASPEN 2008a-b, UPA-BUA 2009).

The economic parameters (growth rates and discount rate) were estimated based on the analysis of the evolution of prices during the past 50 years (Dexia Bank 2007, De Troyer 2007, ABEX 2009) and of predictions for the coming years (Federaal Planbureau 2007, D'haeseleer 2007). The assumptions are summarised in TABLE II. Sensitivity analyses were performed to determine the influence of these parameters on the results. The results, however, proved to be fairly robust (Allacker 2010).

TABLE II The economic parameters applied for the basic and sensitivity scenarios (real rates) (Allacker 2010, 92).

	basic scenario	scenario 1	scenario 2
discount rate	2%	**4%**	2%
growth rate energy	2%	2%	**4%**
growth rate material	0%	0%	0%
growth rate labour	1%	1%	1%
ABEX	0,5%	0,5%	0,5%

e. Performance evaluation

The architect and contractor implicitly consider performance alongside financial cost (and environmental impact). Within the optimisation analysis of this research, there is nobody to watch over the performance. A quality evaluation is thus a necessary aspect of the sustainability analysis. Quality is, however, a subjective aspect and cannot be assessed in an objective way. An existing method for the quality evaluation of housing in Belgium, entitled '*Method for the evaluation of the quality of dwellings in the design phase*' (Ministerie van de Vlaamse Gemeenschap 1991) was chosen as starting point. The method is, however, adapted to avoid double-counting with the cost and environmental impact assessment of the dwellings and to update some of the indicators based on current regulations. The (adapted) method is based on a multi-criteria analysis (MCA) and considers dimensional, functional and technical characteristics of the dwelling and includes an evaluation of the surroundings of the dwelling.

Since subjective weighting factors need to be defined for an MCA, a sensitivity analysis was conducted by defining four sets of weighting factors based on four different household profiles. The Analytical Hierarchy Process (AHP) technique was used to determine these weighting factors (Schreck 2002).

For the optimisation of the dwellings, it was assumed that all defined dwelling variants had a good technical quality. They fulfilled the current norms and regulations. A quality evaluation was therefore only made to compare the dimensional and functional characteristics of the dwellings.

f. Optimisation

Several methods exist for multi-objective decision problems, such as radar plots, cost-benefit analysis and Pareto optimisation, and multi-criteria analysis. Pareto optimisation (Marler and Arora 2004, Verbeeck 2007) was selected as most appropriate method to search for priorities to efficiently move towards more sustainable dwellings. The optimisation concerns a marginal comparison of costs (and/or benefits) in order to select the optimal ones out of a range of proposed options. The result is a set of optima (improvements) starting from a reference and is graphically presented by the Pareto front (FIGURE 2).

A population of options was generated for the analysed dwelling by considering all possible combinations of predefined technical solutions (current technology) for each of the building elements. The following objectives were considered for the cost optimisation:

- Lowest lifecycle financial (LF) cost and lowest financial investment (IF)
- Lowest lifecycle environmental (LE) cost and lowest environmental investment (IE)
- Lowest lifecycle total (LT) cost and lowest total investment (IT)

Beside a detailed study of the retrieved optima on the Pareto set, the obtained Pareto sets for the above defined objectives were compared in order to investigate if the decisions were identical. As mentioned before, in order to enable a comparison of the different dwellings, the qualities were included in the optimisation procedure. In contrast to the cost optimisation, the objectives were now maximisation on the one hand (quality) and minimisation on the other hand (cost).

The retrieved Pareto fronts typically consisted of a steep vertical decline for the options with a low initial cost and of a more horizontal course for the higher investments. This is illustrated in FIGURE 2. The option with the lowest lifecycle cost (option 'A') was defined as the 'absolute' optimum. However, this option requires a high extra investment for a relatively small reduction in the lifecycle cost compared to option 'B' at the end of the steep vertical decline.

Therefore, the 'absolute' optimum can be questioned. Option 'B' can therefore be seen as the most interesting (without budget restriction) and was defined as the 'sub-optimum'.

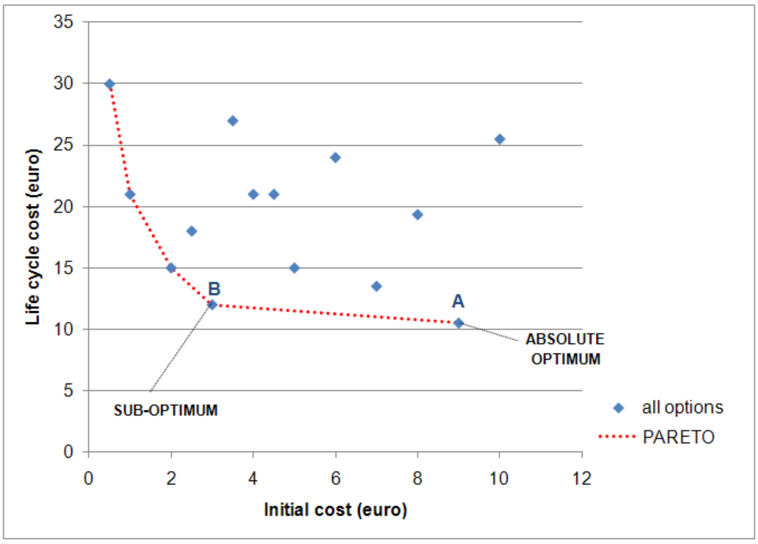


FIGURE 2 Definition of 'absolute optimum' and 'sub-optimum' for a typical Pareto front (Allacker 2010, 187).

g. Assessment steps

The developed methodology was translated into an assessment model which was developed to be used only by the three project partners. The tool was in a first step implemented for the analysis of several building elements, followed by an implementation at the building level of newly built dwellings and renovation cases. In addition, the developed tool was used for the evaluation of a number of current policy measures related to sustainable building. These steps are shortly described in the subsequent paragraphs.

i. Development of an assessment tool

Flexibility, transparency and applicability during the different design phases were three important characteristics which were strived for when translating the developed methodology in an assessment tool. Flexibility was important in terms of changing insights in future concerning environmental indicators, monetary values, scenarios (transport, EOL, cleaning, maintenance, and replacement frequencies) and in terms of expansion of the currently considered materials, work sections, elements and building types. Transparency was important to allow a correct interpretation of the results. In order to develop a tool that is applicable during the different design phases, the tool is hierarchically structured according to the element method for cost control (a.a. 1968, Stichting Bouwkwaliteit 1991). Building elements are independent parts of the building the designer is accustomed to work with. Examples are foundations, ground floor and outer walls. This hierarchical structure allows to make a detailed assessment at the level of a single element or to assess the whole building.

During the first design phases, average costs for each element can be assumed, while more detailed costs can be calculated later on in the design process. Both the financial and environmental cost databases are structured according to the BB/SfB-plus code (De Troyer et al. 1990, De Troyer 2008) which means a unique code is assigned to each work section. This allows easily looking up data and is a necessary characteristic for the modelling of the tool.

Because the EPB characteristics (K and E value) are meanwhile so well-known in Europe, the calculation of these values (developed previously by K.U.LEUVEN) was integrated in the tool and reported for each analysed dwelling variant. The integration of the EPB in the assessment tool moreover limits the necessary input time since now the same tool calculates both costs and EPB results (otherwise the same data had to be input twice).

ii. Building element assessment

The building elements were investigated prior to the analysis at the dwelling level in order to limit the population to be investigated at the higher building level. Thirteen elements were analysed in detail: inner and outer walls, floor on grade, intermediate floors, windows (only frames), flat and pitched roof, the technical services for heating, domestic hot water production and ventilation, rainwater and wastewater systems, photovoltaic panels, elevators for apartment buildings and outdoor floors (finishes).

As defined within the BB/SfB system, each of the elements is composed of a primary layer, finishing layers and sometimes an insulation layer. The analysis was carried out for each of the layers separately in order to gain insight in the importance of each of these. Moreover, a reference for each of the elements was defined which represents common practice to date (construction technique and insulation level). Comparison of the Pareto optima with this reference gave insight into the optimisation potential of common practice to date. Only alternatives available on the current building market were included, limited to those variants of which both financial and environmental data were available.

The heating demand at the element level (for the building skin elements) was limited to transmission losses and was estimated based on the equivalent degree day method (DPWB 1984). The number of equivalent degree days was assumed 1200 based on an extended analysis of a detached and terraced house (Allacker 2010). This value corresponds to a well insulated dwelling and thus enables to determine the optimal insulation thickness of the different elements, assuming that the other elements are also well insulated.

The functional unit differs per element and equals one unit of element, such as, for example, 1m foundation, 1m² of outer wall, 1m² of horizontally projected roof and 1 heating system. The element analyses were performed for a building life span of 60 years considering replacements of the elements with a shorter service life. A sensitivity analysis of 120 years was also made.

iii. Assessment of newly built dwellings

For the analysis of the newly built dwellings, 16 representative dwellings were selected (FIGURE 3). These differ in typology (detached, semi-detached, terraced and apartments) and in construction period (before 1945, 1945-1970, 1971-1990 and 1991-2007) in line with statistics regarding the Belgian dwelling stock. The difference in construction period is only of importance in terms of building size and geometric characteristics because the analysis of each of the 16 dwellings focuses on newly built dwellings.
However, the costs-in-use and EOL cost of the original dwelling were also calculated in order to gain insight in the difference in remaining costs for further use of the original dwellings compared to the lifecycle cost of current standard and optimised variants. Since in reality many dwellings have undergone one or more renovation campaigns, the above comparison is only a rough estimation. A more detailed investigation of renovated dwellings was executed in a separate analysis (see next section (2-0)).

For the analysis of the dwellings, building parts with a shorter service life than the service life of the dwelling were assumed to be replaced by identical solutions. Floor tiles with a service life of 20 years were for example were replaced by identical tiles after 20 years.

The number of dwelling alternatives rapidly increased when combining different options of all elements occurring in the dwelling. To limit this number of combinations, only a selection of the considered element alternatives were analysed at the building level (TABLE III).

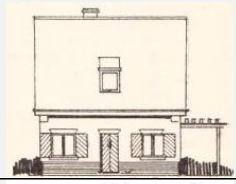
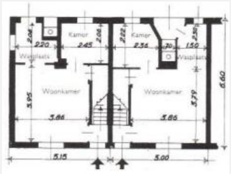
	< 1945	1945 - 1970	1971 - 1990	1991 - 2007
detached house				
semi-detached house				
terraced house				
apartment				

FIGURE 3 Overview of the sixteen representative dwelling types (Allacker 2010, 161)

TABLE III Overview of the analysed variants of the building elements for the assessment at the building level (Allacker 2010, 264)

	SOLID	SKELETON
FOUNDATION	FOUND1: in situ concrete	
FLOOR ON GRADE	GRFL0: concrete slab - no insulation - ceramic tiles GRFL1: concrete slab - 3 cm PUR foam - ceramic tiles GRFL2: concrete slab - 10 cm PUR foam - ceramic tiles GRFL3: concrete slab - 21 cm PUR foam - ceramic tiles	
OUTER WALL	OW0: building bricks - no insulation - brick veneer OW1: building bricks - 7,5 cm rockwool - brick veneer OW2: building bricks - 14 cm rockwool - brick veneer OW3: building bricks - 20 cm rockwool - brick veneer OW8: building bricks - 14 cm EPS - stucco OW9: building bricks - 20 cm EPS - stucco	OW10: timber frame + 14 cm cellulose - brick veneer OW17: FJI + 24 cm cellulose - larch OW18: FJI + 30 cm cellulose - larch OW19: FJI + 36 cm cellulose - larch OW20: FJI + 41 cm cellulose - larch OW17b: FJI + 24 cm cellulose - brick veneer OW18b: FJI + 30 cm cellulose - brick veneer OW19b: FJI + 36 cm cellulose - brick veneer OW20b: FJI + 41 cm cellulose - brick veneer
PITCHED ROOF	PR0: rafters + purlins - no-insul PR1: rafters + purlins - 8 cm rock wool PR3: rafters + purlins - 22 cm rock wool PR4: rafters + purlins - 26 cm rock wool PR5: rafters + purlins - 30 cm rock wool PR7: rafters + purlins - 38 cm rock wool PR0b: rafters - no insulation PR9: rafters - 10 cm rock wool PR10: rafters - 14 cm rock wool PR11: rafters - 18 cm rock wool PR12: rafters - 20 cm rock wool PR13: rafters - 24 cm rock wool PR14: rafters - 28 cm rock wool PR15: rafters - 30 cm rock wool	
FLAT ROOF	FR0: hollow concrete slab - no insulation - EPDM FR1: hollow concrete slab - 16 cm rock wool - EPDM FR2: hollow concrete slab - 24 cm rock wool - EPDM FR3: cellular concrete slab - 14 cm resol - EPDM FR4: cellular concrete slab - 20 cm resol - EPDM FR5: cellular concrete slab - 28 cm resol - EPDM	FR9: FJI + 24 cm cellulose + 6 cm resol - EPDM FR10: FJI + 30 cm cellulose + 8 cm resol - EPDM FR11: FJI + 36 cm cellulose + 10 cm resol - EPDM FR12: FJI + 41 cm cellulose + 12 cm resol - EPDM
LOADBEARING INNER WALL	LIW1: bricks - gypsum plaster	LIW4: timber frame + rockwool - gypsum board
NON-BEARING INNER WALL	NLIW3: metal stud + cellulose - gypsum board	
FLOOR	FL1: hollow concrete slab - carpet	FL2: wood beams - carpet
WINDOW	W1: meranti frame (standard) + standard double glazing + aluminium glass profile W2: meranti frame (standard) + thermally improved glazing + aluminium glass profile W3: meranti frame (insulated) + thermally improved glazing + thermally improved glass profile W4: meranti frame (insulated) + triple glazing + thermally improved glass profile	
SERVICES	condensing gas boiler + low temperature panel radiators + coupled instant hot water production + ventilation C	
NUMBER OF VARIANTS (MAXIMUM)	**13.440**	**8.064**

The selection was based on the results of the optimisation at the element level and on the implementation to one dwelling. A differentiation was made between solid and skeleton variants and these were separately optimised. This resulted in two Pareto fronts (one for solid and one for skeleton variants). Each option situated on the Pareto fronts is analysed (and reported) in detail.

The functional unit at this level equals 1 m² of floor area. To avoid the phenomenon that larger dwellings lead to lower impacts per m² floor, the functional unit was also changed to one dwelling and to one inhabitant (only for comparison between the dwellings).

iv. Assessment of renovation measures

The aim of the analysis of renovation measures was twofold. A first objective was identifying the order of priority of different renovation measures. The second aim was to investigate if further use of the non-renovated dwelling, renovation of existing dwellings or new construction is most preferred. The above objectives were analysed from the viewpoint of the building owner.

The first objective was addressed by analysing a number of renovation measures for two of the sixteen representative dwellings, i.e. a terraced dwelling, built before 1945, and a detached dwelling, built in the period 1971-1990. These dwellings were chosen because of their large share in the existing dwelling stock and their differing characteristics (e.g. roof type, insulation level and compactness). The reference dwellings were composed according to common practice within the considered building period. A number of frequently occurring renovation measures were identified and analysed by comparing the lifecycle cost of the renovated dwelling to the non-refurbished variant. Based on this comparison, the (combinations of) measures leading to the highest reduction in financial, environmental and/or total lifecycle cost for the smallest increase in initial cost (order of efficiency) were identified.

The second objective was addressed by comparing the initial and lifecycle financial, environmental and total costs of all non-renovated, renovated and newly-built dwelling variants. This enabled to determine which solution - i.e. further use of the dwelling without any refurbishment, renovation of some parts of the dwelling or new construction - is preferred from both a financial and an environmental point of view, as well as from an overall perspective.

The analysis of the original non-refurbished dwellings was restricted to the remaining future costs. In consequence, nor the financial cost nor the environmental impact for building the original dwelling were taken into account. This approach was maintained for the replacement of building parts, which did not yet reach the end of their service life.

In accordance to the analysed service life of the newly-built dwellings, a time period of 60 years was considered. This choice was based on the fact that the heating cost contributes most to the environmental cost, while the periodic costs for cleaning, maintenance and replacements contribute most to the lifecycle financial cost.

The relative importance of the initial cost is thus rather small and would only decrease when prolonging the service life. Furthermore, a time perspective of 60 years seems already quite long from the viewpoint of the building owner. A sensitivity analysis for a prolonged service life of 120 years was, however, added.

For the assessment of the refurbishment of dwellings, some methodological aspects differed from the analysis of the newly-built dwellings. The initial financial and environmental costs of the renovated dwellings were limited to the investment costs for the refurbishment measures and the necessary demolition activities. For the calculation of the lifecycle costs, these initial costs were added to the costs-in-use and the EOL costs of the whole renovated dwelling. The financial investment costs for renovation were assumed to be on average 3% higher than for new constructions and a VAT of 6% instead of 21% was used.

v. Evaluation of current policy measures

The SuFiQuaD model was used to evaluate financial incentives for stimulating environmental improvements in dwellings. The need for these incentives to make the investments attractive and their justification through the benefits they provide for society were evaluated. The procedural steps were:

1. First of all, it was investigated whether the measure is beneficial for society from an environmental perspective. If not, there is no justification to give any incentive on the basis of environmental considerations.
2. Secondly, the financial cost or benefit of the measure for the end-user was determined from a lifecycle perspective.

Several outcomes can occur:

3. The measure is **attractive** on a strict financial basis: in principle no incentive is needed, as market forces point in the right direction and over-subsidizing is undesirable. This point of view is mentioned, for example, in a recent study for VEA, the Flemish Energy Agency (Moorkens 2010).

   Nevertheless, there still can be barriers for end-users to implement the measure, like lack of information, lack of money for investment, small financial benefit (e.g. very long payback time), etc. Authorities could help through information campaigns, provision of green loans, but even financial incentives can be considered, especially when the benefits for society in terms of external cost savings are very high. As a leading principle, the maximum allowed incentive should be limited to the environmental benefit for society. To avoid rebound effects, it can be justified to reduce this maximum incentive with the private benefit.

4. If the measure is **not attractive** from a financial perspective for the end-user, but creates a benefit for society larger than the cost for the end-user, a financial incentive can be justified. The maximum allowed incentive should be limited to the environmental benefit for society.

The SuFiQuaD evaluation is based on financial and environmental external costs within the building sector. Authorities should also balance the effects of financial incentives in the building sector with incentives for other sectors, such as transport, agriculture and industry.

Furthermore, there exist other arguments for authorities to create financial incentives for energy saving measures in a wider societal sustainability perspective, like: security of energy supply, local employment, economic policy (incl. export and innovation). This point of view is mentioned in a recent advice on green certificates from the social economic committee in Flanders to the Minister of Energy (SERV 2010).

The results of the assessment steps are elaborated in section 3, indicating the specific output. The policy recommendations formulated based on the findings are described in section 4.

3. RESULTS

a. Assessment method and tool

The developed assessment method enables an LCA of dwellings considering both financial and environmental external costs. The implementation of the method enables to define actions in order of priority to move towards a more sustainable dwelling stock in Belgium. Its originality and importance lies in the integration of costs, impacts and performances, its comprehensiveness (lifecycle, building level, more than energy related aspects) and its flexibility (e.g. adaptability based on new insights in the future). The developed methodology is described in detail in several internal research reports and publically available documents (e.g. PhD dissertation, papers in proceedings of international conferences and articles in international journals (in reviewing process)).

The developed assessment tool was proved to be powerful through the detailed analysis of building elements, buildings and current policy measures. It does not only allow to analyse one single building or building element in detail, but also to optimise several variants of this building or building element. The tool can be used during the different phases of the design process by using predefined elements as a first approximation and specific elements later on in the design process. The extended databases allow assessing most building materials and products on the current market. The tool allows an assessment that is more extended than the current energy estimations of buildings. Since the EPB is incorporated in the tool, the need for double input to calculate the obliged EPB values is eliminated.

Outputs:

i. Internal research reports

- Allacker, K., De Troyer, F. and Spirinckx, C. (2007). Note on optimising economic, environmental and quality aspects, BELSPO, 132 pages.
- Spirinckx, C., De Nocker, L., Liekens, I. and Vanassche, S. (2007). Note on monetary valuation of environmental impacts, BELSPO, 48 pages.
- Spirinckx, C. and Putzeys, K. (2007). Note on LCA data in view of the project, BELSPO, 36 pages.
- Putzeys, K. (2007). Note on European research and standardisation, BELSPO, 126 pages.
- Spirinckx, C., Vercalsteren, A. and Putzeys, K. (2008). Note on LCA data in view of the project – update, BELSPO, 41 pages.
- Putzeys, K. (2008). Note on LCC, BELSPO, 15 pages.
- Spirinckx, C., De Nocker, L., Liekens, I. and Vanassche, S. (2008). Note on monetary valuation of environmental impacts - update, BELSPO, 50 pages.
- Allacker, K. and De Troyer, F. (2008). Note on quality evaluation, BELSPO, 35 pages.

- Putzeys, K., Vekemans, G., Spirinckx, C. and Allacker, K. (2008). Interim note on extreme cases, BELSPO, 69 pages.
- Allacker, K., De Troyer, F., Putzeys, K., Vekemans, G. and Spirinckx, C. (2008). Final note on extreme cases, BELSPO, 139 pages.
- Desmedt, J., Cyx, W. and Vekemans, G. (2008). Note on technical solutions, BELSPO, 21 pages.
- Trigaux, D., Putzeys, K., Spirinckx, C., Demuynck, T., Delem, L., Janssen, A., Vrijders, J., De Troyer, F. and Vercalsteren A. (2009). Note on elaboration of refined methodology and work instrument, BELSPO, 78 pages.
- Putzeys, K. (2010). Note on elaboration of quality evaluation, BELSPO, 17 pages.
- Janssen, A., Delem, L., Allacker, K., De Troyer, F. and Debacker, W. (2010). Final report on methodology – focus on renovation – plus future prospects, BELSPO, 71 pages.

ii. PhD dissertation:

Allacker, K. (2010). Sustainable building: The development of an evaluation method. Doctoral dissertation, Katholieke Universiteit Leuven, Leuven, Belgium.

iii. Other publications: see section 6

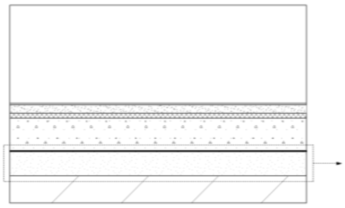
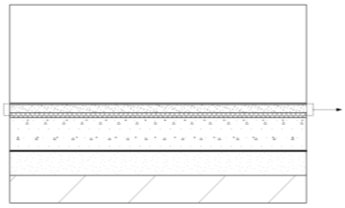
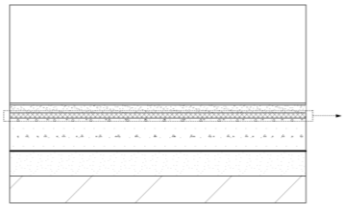
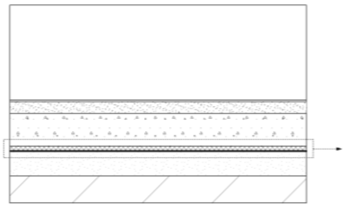
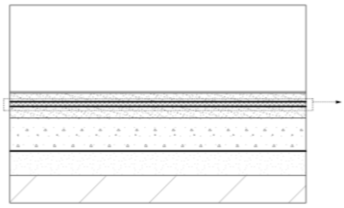
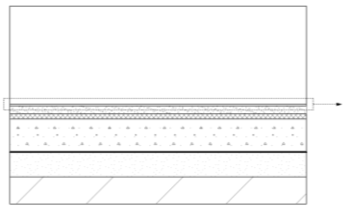
iv. Sustainability assessment tool for building elements and dwellings (extendable for other building types). The tool can be used by the project partners, but is not user friendly for a third party and protected for consequences of unrealistic input.

b. Building element assessment

In the subsequent paragraphs, the most important findings of the element analyses are summarised. It does not concern an exhaustive reproduction of all assumptions and findings, because these are too extended for this end report. For a more detailed elaboration on each of the elements, the outputs listed at the end of this section can be consulted. It concerns internal research reports, the PhD dissertation of Allacker (2010), papers in proceedings of international conferences and articles in international journals (in reviewing process).

Floor on grade

Several alternatives for the floor on grade were analysed (see FIGURE 4). As the figure illustrates, the analysis was done per layer of the floor (floor bed filling, screed, insulation, finishing) keeping the other layers unchanged.

floor composition for the optimisation of the layer indicated	options analysed for the specific layer
floor bed filling ceramic tiles - 1 cm screed cement based - 5 cm PUR foam - 3 cm concrete slab (reinforced) - 15 cm PE sheet floor bed filling 	- compacted sand: 10 cm - gravel: 10 cm - expanded clay aggregates: 10 cm - concrete: 5 cm
screed ceramic tiles - 1 cm screed PUR foam - 3 cm concrete slab (reinforced) - 15 cm PE sheet compacted sand - 10 cm 	- cement based: 5 cm - anhydrite binder - 5 cm - insulating screed, EPS aggregates - 5 cm - insulating screed, EPS aggregates - 10 cm
insulation - PUR foam ceramic tiles - 1 cm screed cement based - 5 cm PUR foam concrete slab (reinforced) - 15 cm PE sheet compacted sand - 10 cm 	PUR foam: 3 - 4 - 5 - 6 - 8 - 10 - 12 - 15 - 18 - 21 cm
insulation - board under concrete slab ceramic tiles - 1 cm screed cement based - 7 cm concrete slab (reinforced) - 15 cm insulation board PE sheet compacted sand - 10 cm 	insulation boards under floor slab: - PUR: 4 – 8 – 10 – 12 – 18 - 24 cm - resol: 4 – 8 – 10 – 12 – 18 – 24 cm - EPS: 4 – 8 – 10 – 12 – 18 – 24 cm - XPS: 4 – 8 – 10 – 12 – 18 -24 cm
insulation - board over concrete slab ceramic tiles - 1 cm screed cement based, reinforced - 7* cm PE sheet insulation board PE sheet leveling course cement based - 7 cm concrete slab (reinforced) - 15 cm PE sheet compacted sand - 10 cm 	insulation boards over floor slab: - PUR: 3 - 5 - 8 - 10 - 15 - 20 cm - rock wool: 3 - 5 - 8 - 10 - 12 - 18 - 24 cm - resol: 4 - 8 - 10 - 12 - 18 - 24 cm - EPS: 4 - 8 - 10 - 12 - 18 - 24 cm - XPS: 4 - 8 - 10 - 18 - 20 cm
floor finishing floor finishing screed cement based - 5 cm PUR foam - 3 cm concrete slab (reinforced) - 15 cm PE sheet compacted sand - 10 cm 	- ceramic tiles - tiles of blue stone (BE) - tiles of blue stone (Asia) - parquet – hardwood (BE mix) (**) - laminate - cork - carpet - linoleum - PUR-floor

(*) The screed thickness varies with the insulation thickness according to the TV193 of BBRI (BBRI 1994, 43).
(**) For the parquet finishing, an extra PE sheet is foreseen above the PUR foam and, consequently, the cement based screed is reinforced.

FIGURE 4 Floor on grade: composition of the floor for the optimisation of the different layers (Allacker 2010, 190)

From the analysis, it was concluded that the costs (both financial and environmental) were mainly determined by the use phase. From a financial point of view, this was mainly due to the cleaning costs, while, from an environmental perspective, heating was contributing most to the lifecycle cost. Compared to current common practice, a financial lifecycle cost reduction of 20% can be achieved, while an environmental lifecycle cost reduction of 60% proved possible. The insulation value and the floor finishing were identified as most important optimisation parameters. The insulation thickness proved to be more important than the choice of insulation material. Depending on the insulation type, a different optimal thickness was determined (see TABLE IV).

TABLE IV Optimal insulation thicknesses from a financial and environmental perspective, indicating the retrieved U-value of the total floor (W/m²K), based on Allacker (2010, 196)

	3 cm	4 cm	5 cm	6 cm	8 cm	10 cm	12 cm	15 cm	18 cm	20 cm	21 cm	24 cm
PUR over	0.37		0.28		0.20	0.17		0.13		0.10		
PUR under		0.33			0.21	0.18	0.15		0.10			0.08
PUR foam	0.38	0.33	0.29	0.26	0.21	0.18	0.15	0.13	0.11		0.10	
resol over		0.32			0.20	0.17	0.15	0.11				0.08
resol under		0.33			0.21	0.18	0.15		0.11			0.08
EPS over		0.39			0.27	0.23	0.21		0.15			0.12
EPS under		0.40			0.28	0.24	0.21		0.15			0.12
XPS over		0.39			0.27	0.23			0.15	0.14		
XPS under		0.40			0.28	0.24	0.21		0.15			0.12
rock wool over	0.46		0.37		0.29	0.25	0.23		0.17			0.13

Financial cost optima

Environmental cost optima

From an environmental point of view, one should insulate more than one should do if only financial costs were considered. The higher insulation thickness according to the financial optimum compared to "thicknesses which are commonly placed to date", requires an extra financial investment of 5% on average and results in a limited reduction of the lifecycle financial cost of 1% on average. However, this increase in insulation thickness results in a reduction in the lifecycle environmental cost of 14% on average. If one opts for even higher insulation thicknesses according to the environmental cost optima, the lifecycle environmental cost is reduced by 18% on average. However, this requires an increase in financial investment of 16% on average (compared to common practice to date) and in an increase in lifecycle financial cost of 2% on average.

The floor finishes, which lead to the lowest lifecycle environmental cost, are linoleum, cork, laminate and carpet. Other criteria, such as for instance hygiene, can of course demand stony materials as floor finishing. Blue stone from Asia is clearly cheaper than the Belgian alternative, but results in a higher environmental cost, because of the extraction processes and necessary transport.

Because it is difficult (if not impossible) to increase the insulation level of the floor on grade during future renovation, it is recommended to invest in a high insulation value of the floor during construction of the dwelling. The floor finishing can more easily be adapted later on and is therefore seen as a second priority.

Non-bearing inner walls

Sixteen wall variants were analysed (FIGURE 5), differentiating between solid and skeleton alternatives. The finishing of the wall was not changed and consists of gypsum plaster for the solid variants and of gypsum board for the skeleton variants. Both the plaster and gypsum board are painted with acrylic paint. The difference in amongst others thermal capacity and acoustical performances is not considered since the importance of these characteristics depends on the application at the building level.

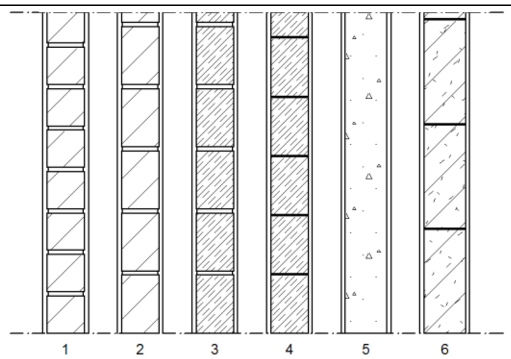
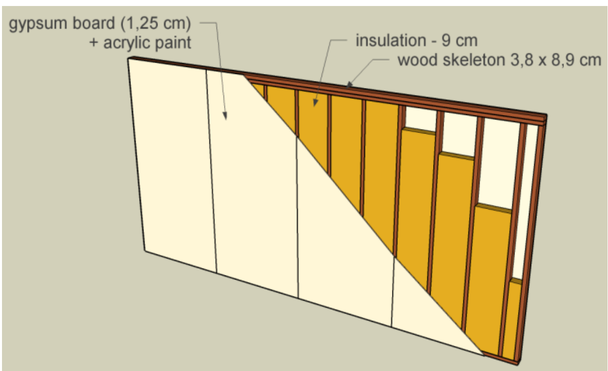
	vertical section 1. building clay bricks (29 x 09 x 09) 2. building clay bricks (29 x 09 x 14) 3. sand-lime brick (29 x 09 x 14) 4. sand-lime brick (29 x 09 x 14), glued 5. concrete (reinforced) 9 cm 6. cellular concrete (60 x 10 x 25)
	Timber frame Metal stud Insulation variants: - cellulose (+ 2 x air-tight sheet) - glass wool - rock wool - wood fibre - hemp cotton

FIGURE 5 Non-bearing inner wall: composition of the solid (top drawing) and skeleton (bottom drawing) variants for the optimisation of the primary layer. (Allacker 2010, 197)

The analysis proved that the replacements during use phase (repainting and re-plastering or replacing the gypsum board) contribute most to the lifecycle financial cost while the initial phase is most important from an environmental perspective. This is illustrated for wall type 1 in FIGURE 6.

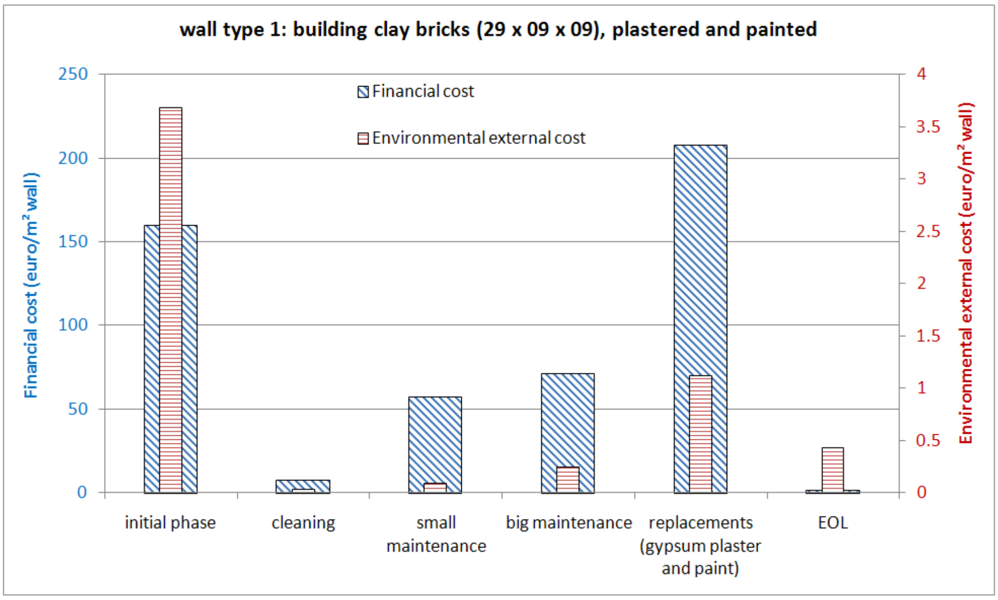


FIGURE 6 Building clay bricks (wall type 1) – contribution of the costs (financial and environmental) for the different life phases and –processes.

The financial investment and lifecycle cost of the skeleton variants proved to be a little lower than of the solid variants, respectively 6% and 10% on average. The difference in financial investment cost between the solid variants is maximum 5%, the difference in financial lifecycle cost 2%, which are both negligible small. The different insulation materials for the skeleton variants did not lead to big differences in financial investment cost (maximum difference of 13%) nor in financial lifecycle cost (maximum difference of 4%). Glass wool was the cheapest, followed by wood fibre, cellulose, rock wool and hemp-cotton.

From an environmental perspective the difference between the solid and skeleton group of alternatives was not as clear as based on financial costs and rather the opposite was noticed: the solid variants led in most cases to a lower lifecycle environmental cost than the skeleton alternatives. The environmental cost of hemp-cotton was remarkably high and proved to be due to the necessary land use for the production of cotton. Similar as for the financial analysis, the metal stud was preferred to the timber frame variants. The higher environmental cost of the timber frame was due to the necessary land use. The uncertainty of the external cost for the impact due to land use is however high and this result should thus be read with caution (it is only valid based on current insights). If land use would not be considered, the timber frame would be preferred to the metal stud variants. The cellular concrete and sand-lime brick alternatives are preferred from an environmental point of view (approximately identical lifecycle environmental cost). The metal stud with cellulose results in an approximately identical lifecycle environmental cost, but requires a higher environmental investment cost (+43%).

The reinforced concrete variant led to the highest lifecycle environmental cost (36% higher than the cellular concrete). In contradiction to the financial cost, the choice of insulation material is important for the lifecycle environmental cost with a difference in minimum and maximum of approximately 30% (not considering hemp-cotton). The order of preference is cellulose, glass wool, rock wool and wood fibre.

Following recommendations can be formulated based on the analysis of the non-bearing inner walls. The difference in lifecycle cost (both financial and environmental) between solid and skeleton variants is on average small and a choice between the two techniques should therefore rather be made based on other criteria such as flexibility (adaptability), acoustical performance and thermal mass. If one opts for a solid construction, cellular concrete and sand-lime brick gain the preference from an environmental point of view. If one opts for a skeleton construction, then the choice of acoustical insulation is of importance for the lifecycle environmental cost. Cellulose gains the preference while hemp-cotton should not be chosen because of the necessary land use for the production of cotton.

Outer walls

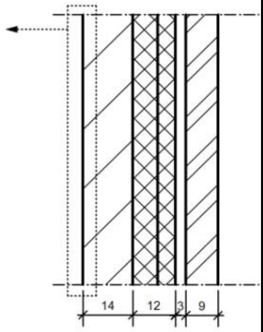
Several outer wall variants were analysed (see FIGURE 7). As the figure illustrates the analysis was done per layer of the wall (internal finishing, loadbearing structure, insulation and external finishing) keeping the other layers unchanged.

The analysis proved that the initial costs were most important from a financial perspective, while both the initial phase and the energy use contributed most to the lifecycle environmental cost. Evidently, the higher the insulation level, the more important becomes the initial phase. Compared to current common practice, the lifecycle financial cost can be reduced by approximately 20%, while a reduction in the lifecycle environmental cost of approximately 40% proved possible. The insulation value and the external finishing were identified as most important optimisation parameters. The insulation thickness was however more important than the choice of insulation material for the lifecycle environmental cost.

INTERNAL FINISHING

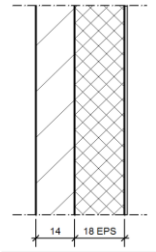
- gypsum plaster + acrylic paint
- gypsum plaster + wall paper
- gypsum board, glued + acrylic paint
- gypsum board on wood* substructure + acrylic paint
- gypsum board on metal substructure + acrylic paint
- MDF on wood substructure + acrylic paint
- wood-fibre cement board on wood substructure + acrylic paint
- cement-fibre board on wood substructure + acrylic paint
- ceramic tiles on gypsum plaster

* 3 variants of wood: current BE mix, 100% native and 100% import

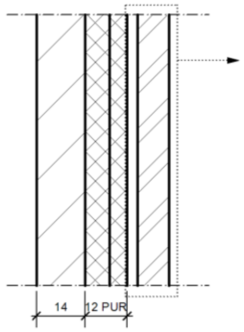


EXTERNAL FINISHING

A) stucco on insulation

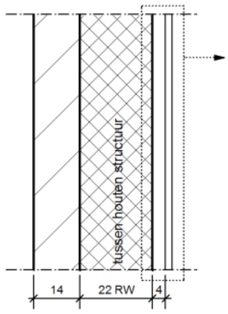


B) outer leave cavity wall:



- brick veneer (9 cm)
- concrete block veneer (9 cm)
- sand-lime stone veneer (10 cm)
- granite veneer (3 cm)
- basalt veneer (1 cm)

C) tiles, board, wood, metal

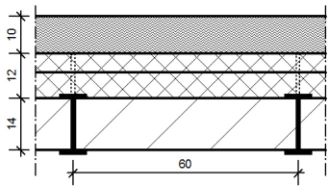


- ceramic facing tiles
- slate tiles
- zinc facing tiles
- fibre cement facing tiles
- ceramic roof tiles
- rock-fibre board
- synthetic board
- fibre cement board
- steel foil
- zinc foil
- aluminium foil
- (un)treated wood planks

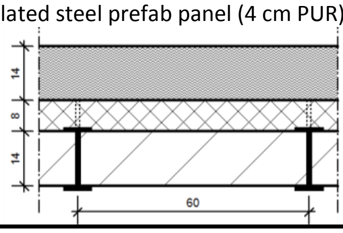
D) prefab panels

(horizontal section)

- concrete prefab panel



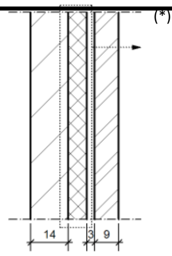
- insulated concrete prefab panel (4 cm PUR)
- insulated steel prefab panel (4 cm PUR)



LOADBEARING STRUCTURE

- building clay bricks (29 x 14 x 14)
- sand-lime bricks, bricklayed (29 x 14 x 14) and glued (30 x 15 x 15)
- perforated building clay bricks, bricklayed (29 x 14 x 14) and glued (29 x 14 x 19)
- concrete blocks (29 x 14 x 19)
- cellular concrete (60 x 15 – 20 – 24 – 30 x 25)
- prefab and in situ concrete (20 cm)
- steel frame (10 cm)
- timber frame (14 cm)
- FJI profiles (24 cm)

CAVITY INSULATION

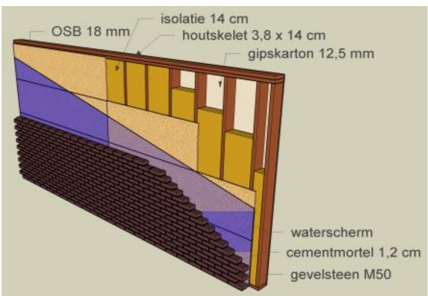


- rock wool: 4 - 5 - 6 - 7 - 10 - 12 - 14 - 16 - 18 - 20 cm
- glass wool: 5 - 6 - 7,5 - 9 - 10 - 12 - 14 - 16,5 - 18 - 20 cm
- EPS: 5 - 6 - 7 - 8 - 9 - 10 - 12 - 16 - 18 - 20 cm
- PUR: 3 - 5 - 7 - 8 - 10 - 14 - 16 - 18 - 20 cm
- XPS: 4 - 5 - 6 - 8 - 10 - 12 - 16 - 20 cm
- cellular glass: 5 - 6 - 7 - 8 - 9 - 10 - 12 - 14 - 16 - 18 - 20 cm
- cellulose flakes: 4 - 6 - 8 - 10 - 12 - 14 - 16 - 18 - 20 - 22 cm
- PUR foam: 4 - 5 - 6 - 7 - 8 - 9 - 10 - 12 - 14 - 16 - 18 - 20 cm

(*) PUR foam without 3 cm air cavity
cellulose flakes between wood structure

SKELETON INSULATION

- timber frame (14 cm)
  - rock wool
  - glass wool
  - wood fibre
  - cellulose flakes
  - PUR foam
- FJI (24 - 30 - 36 - 41 cm):
  - rock wool
  - cellulose flakes



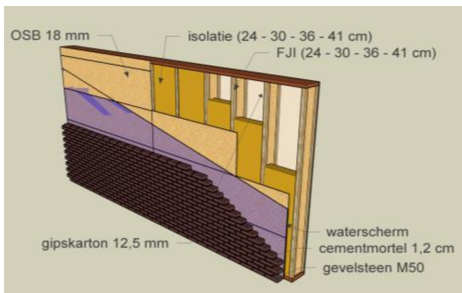


FIGURE 7 Outer wall: composition of the wall for the optimisation of the different layers

Based on financial costs, a different optimal thickness is determined for the different cavity insulations considered (TABLE V). From an environmental point of view, the highest considered thickness proved to be the most preferred.

TABLE V Optimal cavity insulation thicknesses based on the financial cost analysis, indicating the obtained U-value (W/m²K) of the wall

	3 cm	4 cm	5 cm	6 cm	7 cm	7,5 cm	8 cm	9 cm	10 cm	12 cm	14 cm	16 cm	16,5 cm	18 cm	20 cm	22 cm
rock wool		0.53	0.46	0.41	0.35				0.28	0.24	0.21	0.19		0.17	0.16	
glass wool			0.46	0.41		0.35		0.30	0.28	0.24	0.21		0.19	0.17	0.16	
EPS			0.46	0.41	0.37		0.33	0.28	0.24	0.21		0.19		0.17	0.16	
PUR	0.48		0.34		0.26		0.23		0.19		0.15	0.13		0.11	0.11	
XPS		0.52	0.45	0.40			0.32		0.27	0.24		0.19			0.15	
cellular glas			0.47	0.42	0.38		0.35	0.32	0.29	0.25	0.22	0.20		0.18	0.17	
cellulose flakes		0.55		0.44			0.37		0.32	0.28	0.25	0.22		0.20	0.19	0.17
PUR foam		0.57	0.49	0.43	0.38		0.35	0.31	0.29	0.25	0.22	0.19		0.17	0.16	

Financial cost optima

The higher insulation thickness according to the financial optimum compared to common practice to date requires an extra financial investment of 3% on average and results in a limited reduction in the lifecycle financial cost of 1% on average. This higher thickness however results in a reduction in the lifecycle environmental cost of 16% on average. The optimal thicknesses from an environmental point of view require an extra financial investment of 12% on average, result in an increase in the lifecycle financial cost of 12% on average, but lead to a reduction in the lifecycle environmental cost of 28% on average. Cellulose flakes proved not to be interesting as cavity insulation because of the necessary extra wood substructure which leads to both high financial and environmental costs.

Cellular concrete blocks – combined with thermal insulation – proved to be the preferred loadbearing structure from a financial perspective (thicker blocks without insulation should be avoided). From an environmental point of view sand-lime bricks and perforated building clay bricks gain the preference.

If one opts for a skeleton structure, from a financial point of view timber frames gain the preference to FJI profiles for small insulation thicknesses while the opposite is true for larger insulation thicknesses. From an environmental perspective, the FJI profiles are always preferred. The 41 cm thick FJI profiles filled with cellulose flakes lead to the lowest lifecycle environmental cost. A similar construction with a lower thickness of 24 cm leads to the lowest lifecycle financial cost.

The external finishing variants leading to the lowest lifecycle environmental cost are stucco on insulation, a brick veneer and synthetic boards. Wood planks lead to a relatively high environmental cost due to the necessary land use.

If the latter would however not be considered (because of the higher degree of uncertainty), then the wood planks would lead to the lowest lifecycle environmental cost. A finishing in zinc or aluminium foil, ceramic facing tiles and a granite veneer lead to high lifecycle environmental costs due to their high initial impact.

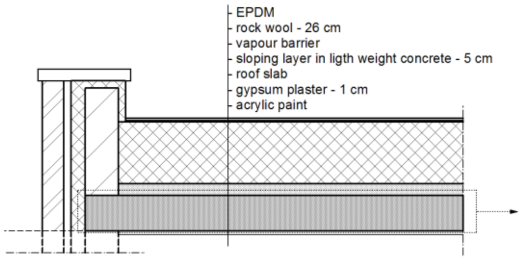
The analysed variants of the internal finishing of the walls did not lead to large differences in lifecycle cost. From a financial perspective, the glued painted gypsum board gains the preference while painted gypsum plaster is preferred from an environmental point of view. The ceramic tiles for wall finishing lead to a high environmental cost but of course have different performances (easier to wash and higher moisture resistance).

Based on the results it can be recommended that for newly built dwellings it is important to foresee a high insulation level for the outer walls since it is difficult (especially for cavity walls) to increase the insulation level later on in the lifecycle during renovation. The external finishing can be adapted more easily later on and is in that sense identified as second priority, although it is advisable choosing a finishing with a low impact right from the start if the budget allows it.

Flat roof

Several alternatives for the flat roof were analysed (see FIGURE 8). The roof was analysed per layer (roof structure, insulation, boarding, external finishing) keeping the other layers unchanged. The interior finishing was not changed since these are similar to the finishing of walls (see outer walls). Moreover, differences in thermal capacity or acoustical or other performances were not considered because their importance can only be evaluated at the building level. From the analysis it was concluded that for currently commonly applied roof constructions, the investment cost represents about 40% and the cleaning, maintenance and replacement cost about 55% of the lifecycle financial cost, while the initial phase and heating both represent about 45% of the lifecycle environmental cost (FIGURE 9). Compared to current common practice a financial lifecycle cost reduction of 10% can be achieved while an environmental lifecycle cost reduction of 50% proved possible with currently available materials and techniques. From a financial point of view, the roof structure is the most important optimisation parameter, while both the insulation and the roof structure are the most important parameters from an environmental perspective.

ROOF STRUCTURE

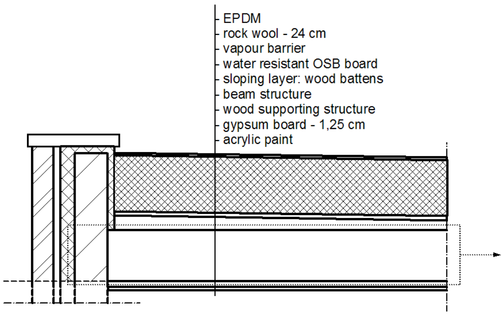


A) solid

- reinforced hollow concrete slab: 16,5 cm
- pre-stressed hollow concrete slab: 12 cm
- cellular concrete slab: 15 cm*
- reinforced concrete slab: 15 + 5 cm
- beams and infill blocks (concrete): 12 cm
- beams and infill blocks (clay): 12 cm
- in situ reinforced concrete: 15 cm

* the cellular concrete slab and the beams with clay infill blocks are foreseen of 22 cm and 24 cm rock wool respectively instead of 26 cm

B) beams + insulation on top

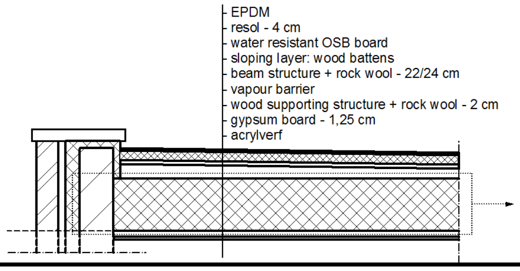


For wood beams:

- -wooden planks
- -plywood
- reinforced wood wool cement board

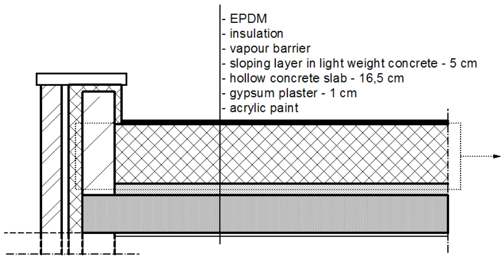
- wood beams: 22 cm
- FJI beams: 24 cm

C) beams + insulation in between



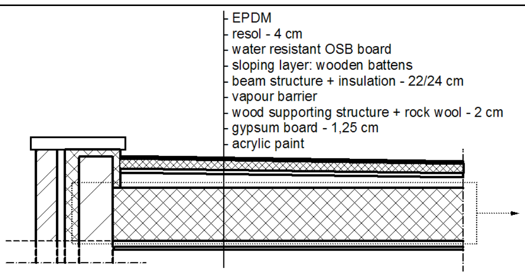
- wood beams: 22 cm
- FJI beams: 24 cm

INSULATION



* On top of the EPS insulation 5 cm gravel is foreseen as protection to high temperatures (melting)

- rock wool: 6 – 10 – 12 – 16 – 20 – 24
- EPS*: 8 – 10 – 12 – 16 – 20
- PUR: 6 – 10 – 12 – 17 – 20 – 24
- wood fibre: 6 – 12 – 18 – 24
- resol: 6 – 10 – 14 – 20



- wood beams + rock wool (22 cm) – for comparative base
- wood beams + cellulose (22 cm)
- wood beams + PUR foam (22 cm)

- FJI beams + rock wool (24 cm) – for comparative base
- FJI beams + cellulose (24 cm)

Although insulation is preferably put above the structure, the option with insulation in between the beams is included to enable the evaluation of insulation alternatives which can only be used between beams.

EXTERNAL FINISHING	**ROOF EDGE** (for EPDM variant)
- EPDM - APP bitumen - PVC	- concrete - blue stone (BE) and (Asia) - aluminium - zinc - polyester

FIGURE 8 Flat roof: composition of the roof for the optimisation of the different layers

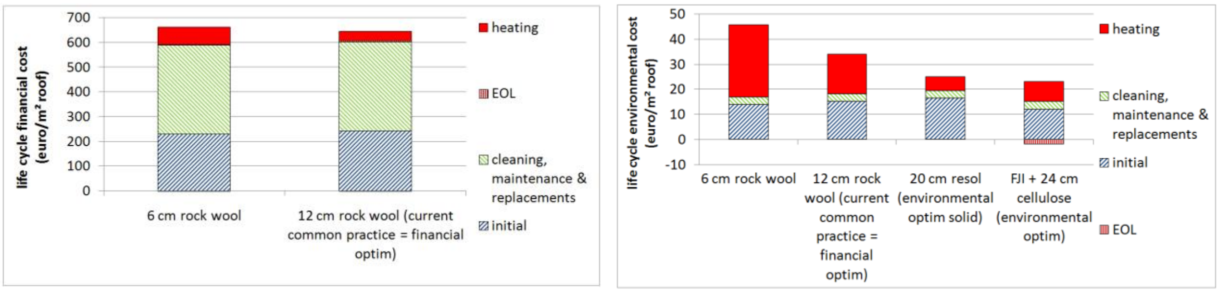


FIGURE 9 Contribution of the different processes to the lifecycle financial (left) and environmental (right) cost

The cellular concrete slab was identified as most preferred solid structure, both based on the financial and environmental analysis. From a financial perspective this optimum is followed by a pre-stressed hollow concrete slab and ceramic beams and infill blocks. From an environmental point of view, the concrete beams and infill blocks are the second preferred option. The wood beams are preferred from a financial perspective, while the FJI beams are preferred based on environmental cost.

The most optimal insulation thickness based on the financial cost optimisation are summarised in TABLE VI These thicknesses are in line with current building prescriptions (EPB). Based on the environmental external cost optimisation however larger thicknesses should be chosen (largest considered thicknesses were identified as optima).

TABLE VI Optimal insulation thicknesses for flat roofs based on the financial cost analysis, indicating the obtained U-value (W/m²K)

	6 cm	8 cm	10 cm	12 cm	14 cm	16 cm	17 cm	18 cm	20 cm	24 cm
rock wool	0.55		0.36	0.30		0.23			0.19	0.16
EPS		0.40	0.32	0.27		0.21			0.17	
PUR	0.41		0.25	0.21			0.15		0.13	0.11
wood fibre	0.63			0.35				0.24		0.18
resol	0.32		0.21		0.15				0.11	

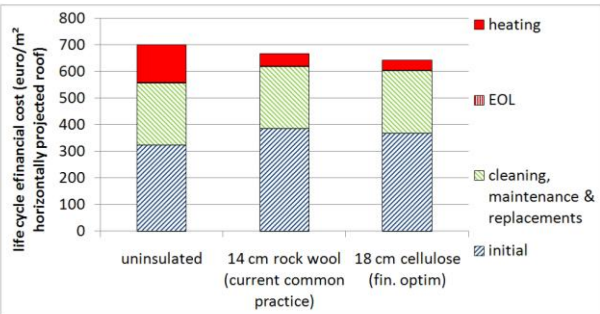
Financial cost optima

The results moreover proved that the insulation thickness is more important than the choice of insulation type. For the insulation on top of the roof structure, resol is most preferred, while cellulose gains the preference for insulation between the beams. The higher optimal thicknesses from an environmental point of view compared to thicknesses according to common practice to date requires an extra investment of 16% on average, results in an increase in lifecycle financial cost of 4% on average, but in a reduction in lifecycle environmental cost of 10% on average.

For flat roofs composed of a beam structure, the insulation is preferably put on top of the structure in order to avoid moisture problems. For large insulation thicknesses this results in an extreme thick roof composition. In low-energy and passive houses, one therefore often opts for insulation between the beams, combined with insulation on top of the beam structure. To avoid moisture problems for such compositions, it is important that the vapour barrier is carefully put in place and that the roof boarding is dry (RH < 80%). The analysis of both options proved that when identical insulation materials are used, the roof with insulation between the beams does not lead to a much lower lifecycle environmental cost. However, if one opts for FJI beams combined with insulation materials meant to be blown in or to be injected (e.g. cellulose flakes), this results in a substantial reduction in the environmental cost. It is however important that these alternatives are combined with insulation put on top of the structure to avoid internal condensation problems.

Pitched roof

Several alternatives for the pitched roof were analysed (see FIGURE 11) The roof was analysed per layer (roof truss, insulation, underlay, external finishing) keeping the other layers unchanged. The interior finishing was not changed since these are similar to the finishing of skeleton walls (see outer walls). From the analysis it was concluded that for currently commonly applied roof constructions, the investment cost represents about 60% of the lifecycle financial cost, while the heating cost - with about 50% - stands for the most contributing factor to the lifecycle environmental cost (FIGURE 10). Compared to current common practice a financial lifecycle cost reduction of 10% can be achieved while an environmental lifecycle cost reduction of 40% proved possible.



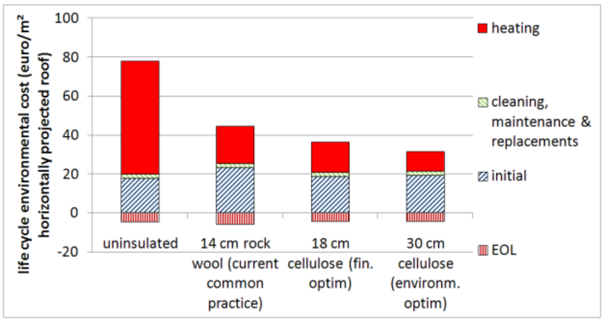
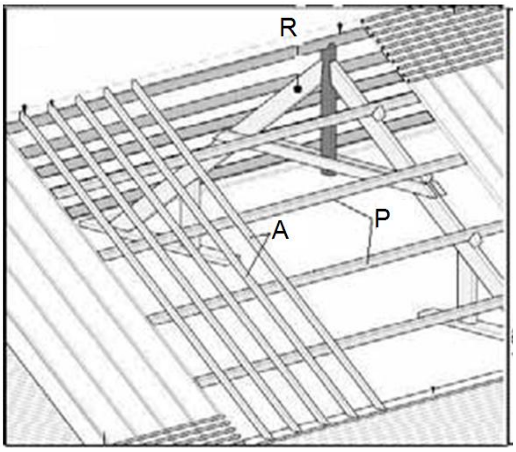
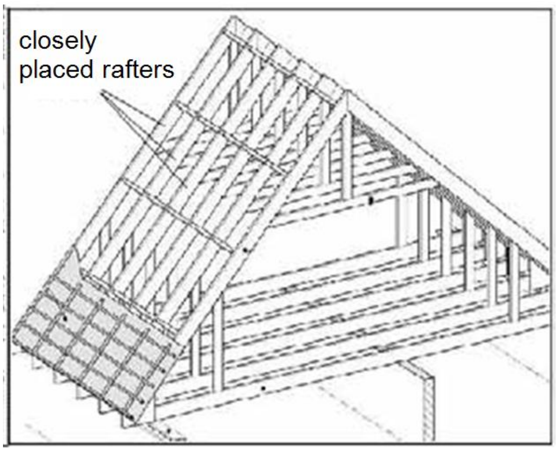


FIGURE 10 Contribution of the different processes to the lifecycle financial (left) and environmental (right) cost

ROOF TRUSS



source: BBRI 1996, 11



source: BBRI 1996, 12

- rafters (R), purlins (P) and arrises (A) – 18 cm rock wool
- rafters and purlins without arrises, prefabricated roof panels – 19 cm rock wool
- rafters (R), purlins (P) and arrises (A) – 30 cm rock wool

- closely placed rafters – 18 cm RW
- closely placed rafters – 30 cm RW

*All variants: - external finishing: ceramic roof tiles
- underlay: wood fibre board
- internal finishing: gypsum board + acrylic paint
except prefabricated roof panels: foreseen of chipboard, acrylic paint as finishing

EXTERNAL FINISHING

(roof truss consisting or rafters, purlins and arrises, wood fibre board as underlay and 22 cm rock wool)

- ceramic roof tiles
- concrete roof tiles
- zinc slate roofing on PEb foil and wood boarding
- slate roofing (native and imported)
- fibre cement slate roofing
- corrugated fibre cement slate roofing
- steel tile roof plate
- aluminium tile roof plate
- wood shingles
- bitumen shingles on wood board

UNDERLAY

(roof truss consisting or rafters, purlins and arrises, ceramic roof tiles as external finishing and 22 cm rock wool)

- wood fibre board
- fibre-cement board
- reinforced wood wool cement board
- PP PE board
- PP foil

INSULATION

(roof truss consisting or rafters, purlins and arrises, ceramic roof tiles as external finishing and wood fibre board as underlay)

- Substructure insulation between purlins: wooden battens (38 x 25 mm) **under** insulation layer:
  - rock wool: 8 - 8+10 - 8+14 - 8+18 - 8+22 - 8+26 - 8+30
  - expanded cork: 8 - 8+6 - 8+10 - 8+16 - 8+20 - 8+22 - 8+26 - 8+30
  - wood fibre: 8 - 8+6 - 8+10 - 8+16 - 8+20
  - cellulose flakes 8 - 8+10 - 8+14 - 8+18 - 8+22 - 8+26 - 8+30
  - PUR foam (high density): 8 - 8+10 - 8+14 - 8+18 - 8+22 - 8+26 - 8+30

- Substructure insulation between purlins: wooden battens (38 mm x thickness insulation) **between** insulation layer
  - rock wool: 8 - 8+10 - 8+14 - 8+18 - 8+22 - 8+26 - 8+30

FIGURE 11 Pitched roof: composition of the roof for the optimisation of the different layers

The insulation value was identified as most important optimisation parameter, both from a lifecycle financial and environmental perspective, followed by the choice of roof covering. The first centimetres of insulation are clearly very important to reduce the environmental external cost (FIGURE 10) right).

A minimal insulation is thus indispensable. The optimal thickness based on financial considerations was identified as 8 cm (insulation between the arrises), except for cellulose flakes with an optimal thickness of 18 cm.

From an environmental point of view, a higher thickness should be foreseen. The optimal thickness varies for the different insulation materials (TABLE VII).

TABLE VII Optimal insulation thicknesses based on the environmental external cost analysis, indicating the obtained U-value (W/m²K) of the roof

	8 cm	8 + 6 cm	8 + 10 cm	8 + 14 cm	8 + 16 cm	8 + 18 cm	8 + 20 cm	8 + 22 cm	8 + 26 cm	8 + 30 cm
rock wool (wood under)	0.39		0.20	0.17		0.15		0.13	0.12	0.11
rock wool (wood between)	0.39		0.22	0.18		0.16		0.14	0.13	0.12
expanded cork	0.40	0.26	0.21		0.17		0.15	0.14	0.12	0.11
wood fibre board	0.39	0.19	0.15		0.11		0.09			
cellulose flakes	0.40		0.21	0.18		0.15		0.14	0.13	0.12
PUR foam	0.35		0.17	0.14		0.12		0.11	0.09	0.08

Environmental external cost optima

These higher thicknesses require an extra financial investment of 10% on average, result in an increase in the lifecycle financial cost of 4% on average, but lead to a reduction in the lifecycle environmental cost of 11% on average. The environmental cost can further be reduced by opting for another insulation material, giving preference to the cellulose flakes, followed by rock wool. Finally, the analysis proved that the way the insulation is put in place (e.g. wooden battens between or under the insulation) is of importance.

The preferred roof coverings are concrete and ceramic roof tiles, both from a financial and environmental perspective. All other considered coverings lead to a higher lifecycle cost. The lifecycle environmental cost is remarkably high for zinc slate roofing (due to a high initial environmental cost) and for the bitumen shingles (due to a shorter life span and thus a higher number of replacements). The wood shingles surprisingly resulted in a high environmental cost, which was due to the necessary land use for the wood. If land use would not be considered (higher level of uncertainty), the environmental lifecycle cost is similar to that of the concrete and ceramic roof tiles.

Intermediate floors

Because the optimisation of intermediate floor variants can to a great extent be based on the analyses of the floor on grade (i.e. floor finishing) and the flat roof (i.e. floor structure and ceiling finishing), this analysis was limited to a selection of five representative variants (see TABLE VIII).

TABLE VIII Intermediate floors: overview of the considered variants

Concrete floor structure	Wooden floor structure
regular concrete floor variant 1	***regular wooden floor variant 1***
• ceramic tiles • cement-based screed • concrete pressure layer • reinforced hollow concrete slab • gypsum plaster • acrylic paint	• ceramic tiles • cement-based screed • PE foil • OSB floor plate • wooden joists and cross beams • gypsum plaster board on wooden substructure • paint
acoustically improved concrete floor variant 1	***acoustically improved wooden floor variant 1***
• ceramic tiles • cement-based screed • PE foil • rock wool insulation • concrete pressure layer • precast reinforced concrete hollow slab • gypsum plaster • acrylic paint	• ceramic tiles • cement-based screed • PE foil • rock wool insulation • OSB floor plate • wooden joists and cross beams • rock wool insulation between joists and beams • PE vapour barrier • gypsum plaster board on wooden substructure • paint
	acoustically improved wooden floor variant 2
	• ceramic tiles • double gypsum board • rock wool insulation • OSB floor plate • wooden joists and cross beams • rock wool insulation between joists and beams • PE vapour barrier • gypsum plaster board on wooden substructure • paint

Two types of floor structure were considered, i.e. a concrete and a wooden structure, differentiating between regular and acoustically improved variants. The latter were included in view of the importance of acoustical performance for dwelling-separating floors within a multi-residential building.

From a financial, environmental and total cost point of view, the concrete floor variants were characterised by lower initial and lifecycle costs than the wooden alternatives. All costs increased when improving the acoustical performance of the floor. The regular concrete floor variant 1 showed the lowest initial and lifecycle costs, while acoustically improved wooden floor variant 2 had the highest initial and lifecycle costs.

Heating and ventilation

Since technical services such as heating and ventilation are closely related to the use phase (energy consumption) of buildings, a single family residential building was selected for the analysis.

The net energy demand – determined amongst others by the insulation level and the air-tightness of the house – however influences the optimal heating services. Therefore, an analysis was made of two variants of the dwelling, namely a variant that corresponds to a non-insulated dwelling (K100) with an air-tightness leading to 12 air changes per hour and a low-energy variant (K20) with an air tightness leading to 0.6 air changes per hour.

An overview of all analysed heating and ventilation variants is given in TABLE IX.

TABLE IX Overview of heating and ventilation variants and related technical components

SPACE HEATING (SH)	**DOMESTIC HOT WATER (DHW)**
Production system	***Production and storage system***
• Oil boiler: *non-condensing and condensing (both floor models)* • Gas boiler: *modulating classic atmospheric (floor model), modulating gas burner (floor model) and modulating condensing (wall model)* • Heat pump: *ground/water (with vertical or horizontal heat exchange), air/water and air/air* – only for K20 dwelling • Pellet furnace: *non-condensing and condensing (both with storage silo and automatic supply)* – only for K20 dwelling	• Independent from SH: o *gas geyser (i.e. without storage)* o *electric boiler, 120l* • Coupled to SH: o *instant (i.e. without storage)* o *storage vessel, 120l for an oil and gas generated furnace or 300l for a heat pump or pellet furnace* o *solar boiler, 120l for an oil and gas generated furnace or 300l for a heat pump or pellet furnace.* – only for K20 dwelling
Distribution system	***Distribution system***
• a double-pipe octopus-system with PE pipes	• PE piping
Emission system	**VENTILATION (VENT)**
• Column radiator: *cast iron or steel plate* • Panel radiator: *steel plate* • Wall convector: *aluminium* • Trench convector: *PET or steel with aluminium or Merbau grid* • Floor heating: *PE-RT on steel mats or on button plate*	• System A: *natural supply and exhaust of air* • System C: *natural supply and mechanical exhaust of air* – only for K20 dwelling • System C+: *natural supply and controlled mechanical exhaust of air* – only for K20 dwelling • System D+: *mechanical supply and controlled exhaust of air with heat recovery* – only for K20 dwelling
Control system	**RELATED TECHNICAL COMPONENTS**
• Manual valves + room thermostat *(MV+RT)* • Manual valves + room thermostat + outside temperature sensor *(MV+RT+OS)* • Thermostatic valves + clock control *(TV+clock)* • Thermostatic valves + clock control + outside temperature sensor *(TV+clock+OS)*	• Exhaust of gasses: *ducts and chimney* • supply of gas and oil: *steel pipes and storage tank* • circulation pump(s) • expansion vessel(s)

Space heating and domestic hot water services were classified according to their constituting sub systems: i.e. production, distribution, emission, control and storage components. Ventilation services were classified according to the type of supply and exhaust of air.

The required capacity of heating production components and sizing of emission devices were calculated in function of the net heating demand of both dwelling variants (K100 and K20). However, for the low-energy dwelling (K20) oil and gas furnaces were over-dimensioned, since small capacities are currently not available on the Belgian market. Small capacity furnaces were identified as an urgent need for low-energy and passive houses and can therefore be formulated as a recommendation towards heating industry and installers. (Debacker et al 2010)

Although heating and ventilation components are only responsible for 2% of the lifecycle environmental costs and 3% of the lifecycle financial costs of both dwelling variants, it does not mean that services are unimportant. Their configuration greatly influences the energy consumption of dwellings. From an environmental point of view, heating (energy) represents the most important part of the lifecycle cost, ranging from 55% (K20) to 78% (K100). This corresponds with 9% (K20) to 18% (K100) of the financial lifecycle cost. Choosing appropriate heating configurations can lead to a reduction of financial lifecycle costs of 10% for the K100 dwelling and of 8% for the K20 dwelling. (Debacker et al 2010)

For the selection of a **space heating (SH)** system a commonly used condensing gas boiler combined with a sophisticated control system (i.e. thermostatic valves combined with a clock and an outside temperature sensor) is preferred based on merely financial costs. Focusing only on the environmentally costs, advanced alternatives such as a heat pump and a condensing pellet furnace can compete with the previously named configuration, but only for a highly insulated dwelling (considering a dwelling life span of 60 years). Although heat pumps are characterised by a higher initial environmental cost, their corresponding lifecycle costs are lower compared to non-renewable production systems. Looking at the total lifecycle costs, once again, the common configuration with the condensing gas boiler is preferred above others for a non-insulated dwelling. A condensing pellet furnace has the lowest total lifecycle costs for the highly insulated dwelling. Based on environmental and total (lifecycle) costs, it was concluded that there is no clear preference for any of the studied emission types. Distribution components have only a minor influence on both financial and environmental costs. Similar conclusions can be drawn for a life span of the dwelling of 120 years.

For the selection of a **domestic hot water (DHW)** system, there is no substantial difference in overall costs between coupled and separate systems over a life span of the dwelling of 60 years. Nor is there a clear preference for solutions with or without heat storage of water. Nevertheless, two distinct observations can be made. Firstly, DHW systems with an electric boiler should be avoided; due to the high energy prices for electricity.

Secondly, the benefit of conserving energy by using a solar boiler is almost cancelled out, due to its higher financial investment cost. Similar conclusions can be drawn for a life span of the dwelling of 120 years.

Environmental and financial costs related to the production, cleaning and replacement of the **ventilation** systems have a relatively small importance of maximum 5% in the lifecycle cost of the dwelling. Ventilation system A seems to be an interesting solution since there is no electricity involved. However, it is not always feasible to achieve normative minimal ventilation requirements by natural ventilation (system A) or sometimes a higher level of control is desired. Looking at alternatives, a ventilation system with natural supply and controlled mechanical exhaust of air (i.e. system C+) offers the best cost reducing measures, since it cuts down electricity for ventilation with 32% compared to system C. Although heating costs are reduced through the use of ventilation system D+ (circa 10% compared to system C and C+), overall lifecycle costs increase with 28% and 41% compared to system C and C+. Electricity costs become more important than heating costs for system D+.

Rainwater and wastewater

Since February 2005 recuperation of rainwater is mandatory in Flanders for every new dwelling and renovation case with a roof surface above $50m^2$. According to the "Code of good conduct" of the Flemish Environment Society this comes along with a rainwater pit of minimum 3000 litre (VMM 2010). In the capital region recuperation of rainwater for all new constructions is imposed since 2006. Although in the Walloon region the installation of a rainwater pit for new construction and renovation is not mandatory, several communes impose it through their own urban settlement regulation.

The Flemish Environment Society defines four areas concerning the treatment of sewage coming from dwellings:

- Area A: public sewage is available; wastewater ends up at a communal treatment unit
- Area B: public sewage is available; wastewater will end up at a communal treatment unit in the future
- Area C: the public sewage is available; wastewater will not end up at a communal treatment unit
- Area where public sewage is not present

Connection to the public sewage system is obligatory for all dwellings in area A, B and C since December 2005. Individual treatment of wastewater is mandatory for all dwellings in area C and areas where public sewage is not present. Based on this classification three cases were analysed:

case 1: connection to public sewage system (area A and B)

case 2: connection to individual water treatment system (area C)

case 3: connection to public sewage and individual treatment system

In all scenarios rainwater conservation was integrated. Only piping outside the dwelling was considered. However, no public sewage pipes were taken into account. TABLE X gives an overview of all considered components related to the rainwater and waste water system.

A life span of 60 years was considered for the dwelling and 30 years for all elements of the rainwater and wastewater system. Water consumption by the dwellers was not considered, but is analysed at the dwelling level (section 3c).

TABLE X Overview of selected components for rainwater and waste water systems

RAINWATER (RW)	WASTE WATER (WW)
• Drains around the dwelling (diameter 100mm) at a depth of 1m • Excavation for trenches and rainwater pit • Filling up with earth, without supply of soil • Rainwater pit in PE, 3000 litres • drain pipes in PE on facade, diameter 100mm, thickness 1,20mm • self cleaning drain pipe filter in PE, diameter 80mm – 100mm • self cleaning rain pit filter in PE • telescopic shaft for rain pit filter in PE, diameter 350mm – 750mm	• excavation for sewage trenches and sewage pit • filling up with earth, without supply of soil • sceptic tank, single chambered in reinforced PE, 2000 litres (only case 2 and 3) • biological wastewater treatment tank, 4000 litres, 1,2l/day sludge • man hole, concrete, • lid for man hole, cast iron • covering plate, cast iron • sewage pipe in the ground, PVC grey, length 3,00m, diameter 200mm and thickness 3,9mm • inspection pit, PVC, height 600mm, inner diameter 400mm • lid for inspection pit, inner diameter 400mm

Rainwater and wastewater services are typically (i.e. for case 1) responsible for 23% of the financial, 9% of the environmental and 23% of the total lifecycle costs of all technical services for a well insulated detached dwelling (K20, condensing gas boiler). The contribution to the financial and total lifecycle cost of the building equals 2%.

All costs per lifecycle phase of the first case – in which rainwater is conserved and the dwelling is connected to the public sewage system and does not require individual wastewater treatment – are clearly lower than the corresponding ones of the two other cases. For the second case – in which no public sewage is available – financial, environmental and total lifecycle costs are respectively 86%, 430% and 90% higher than the first case.

For the third case – in which both types of wastewater systems are combined – financial, environmental and total lifecycle costs are respectively 117%, 453% and 121% higher than the first case. Summarised, connection to the public sewage system is recommended.

Photovoltaic panels

In this section lifecycle costs of typical photovoltaic (PV) systems are compared with the referential Belgian central electricity supply for a dwelling life span of 60 years. A life span of 20 years was defined for the PV panels and of 10 years for the converter. Because preliminary analyses revealed that the life span of PV systems plays an important role in the cost profile, sensitivity analyses of a panel life span of 15 and 30 years were included. An overview of the studied alternatives is shown TABLE XI.

TABLE XI Overview of studied variations for photovoltaic systems (orientation south, no shading obstructions)

PHOTOVOLTAIC SYSTEM	
• capacity: o *900Wp (7,5m²)* o *2400Wp (20,3m²)* o *4800Wp (40,6m²)* • slope: o *45° (pitched roof)* o *32° (flat roof)*	• life span of PV system: o *20 years (standard)* o *15 years (reduced)* o *30 years (extended)* • end-of-life scenario: o *land-filling* o *recycling*

For consistency reasons prices for 2008 were used similar to the other analysed elements. However, the latest evolutions on the financial market indicate that investment costs for PV panels have drastically dropped: from approximately 5,97€/Wp at mid 2008 to 3,55€/Wp at the beginning of 2010 (Aspen 2008a, Solart Systems 2010). In section 3-e (Evaluation of current policy measures) current investment prices of PV panels are related to financial support of the government.

From a financial point of view, all analysed PV systems were more expensive than central electricity supply. The higher cost was due to the investment and replacement costs of the PV systems. Even for an increased life span of the PV system, they resulted in net financial losses (no policy incentives considered).

From an environmental point of view, PV systems with a standard and extended life span created a net lifecycle benefit. The bigger the installation, the higher the profits compared to the centralised production of electricity. Partially recycling of panels and converters at the end of their use period increased the environmental benefits slightly. For small PV installations with a reduced life span of 15 years the potential environmental gains became marginal or negative.

Due to the dominance of the financial cost in the total lifecycle profile, the environmental cost benefits of PV systems can rarely be matched up with the total cost benefits of central electricity supply. Even when prices of beginning 2010 were considered, there was no net lifecycle gain for a standard PV life span of 20 years. Indicative prices of beginning 2011 showed however that a lower total lifecycle cost compared to central electricity supply is possible in the near future. (see section 3-e)

Window frames

The element analysis of the windows was limited to the window frames because glazing alternatives can only be analysed at the building level taking into account solar gains. The glazing was assumed to be normal double glazing (U = 2,9m²K/W).

Eight window frames were compared: aluminium, PVC, Afzelia and Meranti in both a standard and thermally improved variant. The U_f values are summarised in TABLE XII.

TABLE XII Window frames: overview of analysed variants with their respective U_f values

Window frame	U_f (m²K/W)
Afzelia standard	1,8
Afzelia thermally improved	0,8
Meranti standard	1,8
Meranti thermally improved	0,74
PVC standard	1,5
PVC thermally improved	0,8
Aluminium standard	2,7
Aluminium thermally improved	1,4

Despite the higher required investment cost, thermally improved window frames are preferred from a financial point of view. The difference in lifecycle cost compared to standard frames was, however, limited (on average -6%). For both the standard and thermally improved frames, there is only one Pareto optimum. The optima, however, differed. The Pareto optimum for the standard frames was Meranti (but only a negligible higher initial and lifecycle cost was noticed for the PVC frame). The most expensive one was aluminium (lower heat resistance and higher initial costs). For the thermally improved frames, the aluminium alternative was identified as Pareto optimum. The second best alternative was again PVC, requiring a 5% higher investment cost, but resulting in an approximately identical lifecycle cost. Afzelia was the most expensive thermally improved frame.

From an environmental point of view, the thermally improved window frames clearly gained preference over standard frames with an average decrease of the lifecycle environmental cost of 58%. For the standard frames, the wooden alternatives were preferred. Aluminium led to the highest environmental investment and lifecycle cost. PVC required the lowest environmental investment cost of all considered thermally improved frames, but led to a slightly higher lifecycle cost than the wooden frames.

Aluminium led to the highest lifecycle environmental cost due to a higher investment cost and a lower heat resistance.

Outdoor floor finishes

Nine floor finishing variants for drives and terraces were analysed (TABLE XIII).

TABLE XIII Outdoor floor finishes: overview of the considered variants

drives		terraces	
loose finishing	• gravel • sand • broken limestone • broken dolomite	**tiles**	• concrete • natural blue stone • concrete grass
clinkers	• concrete • ceramic		

From a financial point of view, outdoor finishing variants with a loose finishing are characterised by much lower initial and lifecycle financial costs than outdoor finishing variants with either clinkers or tiles. Quality differences should be evaluated on building level and are thus not considered here. The financially best scoring variants (Pareto optima) were gravel or sand. The variants with the highest initial and lifecycle financial costs were natural blue stone tiles, ceramic and concrete clinkers. The higher lifecycle financial costs for clinkers and tiles were due to both higher initial costs (e.g. extra sub-layer required, more expensive upper layer) and higher periodic costs for cleaning, maintenance and replacements.

From an environmental point of view, a similar trend was noticed. Outdoor finishing variants with a loose finishing had much lower initial and lifecycle environmental costs. As was also the case for the financial costs, the environmentally best-scoring variant (Pareto optimum) was gravel, closely followed by sand. The outdoor finishing variants with the highest initial and lifecycle environmental costs were ceramic and concrete clinkers and concrete grass tiles.

Outputs:

i. Internal research reports

- Tomasetig, B., Spirinckx, C., Allacker, K and Putzeys, K. (2008). Note on selection of extreme types, BELSPO, 75 pages.
- Putzeys, K., Vekemans, G., Spirinckx, C. and Allacker, K. (2008). Interim note on extreme cases, BELSPO, 69 pages.
- Allacker, K., De Troyer, F., Putzeys, K., Vekemans, G. and Spirinckx, C. (2008). Final note on extreme cases, BELSPO, 139 pages.
- Putzeys, K. and Janssen, A. (2008). Note on selection of representative element types, BELSPO, 32 pages.

- Putzeys, K., Janssen, A., Allacker, K., De Troyer, F. and Debacker, W. (2010). Intermediate note on representative cases, BELSPO, 261 pages.
- Allacker, K., De Troyer, F., Janssen, A., Debacker, W. (2010), Final note on representative cases, BELSPO, 203 pages.

ii. PhD dissertation:

Allacker, K. (2010). Sustainable building: The development of an evaluation method. Doctoral dissertation, Katholieke Universiteit Leuven, Leuven, Belgium.

iii. Other publications: see section 6

c. Assessment of newly built dwellings

In the first part of this section the assessment and results of one dwelling are elaborated in detail to illustrate the approach and to enable a correct interpretation of the results of all 16 cases studies, summarised in the second part of this section. Since the first part of this section (detached dwelling, type 1 (period before 1945) is an extract out of the PhD dissertation (Allacker 2010, 265 to 274) any citations should be made to the original document. For a detailed description of the assessment of all other cases the PhD dissertation of Allacker (2010) can be consulted.

Detached dwelling, type 1 (period before 1945)

For this detached dwelling (FIGURE 12) 21.504 variants were analysed (13.444 solid + 8.064 skeleton). Sensitivity analysis of the life span (30 – 60 – 120) and of the economic parameters (two alternatives) led to a total of 193.536 simulations.

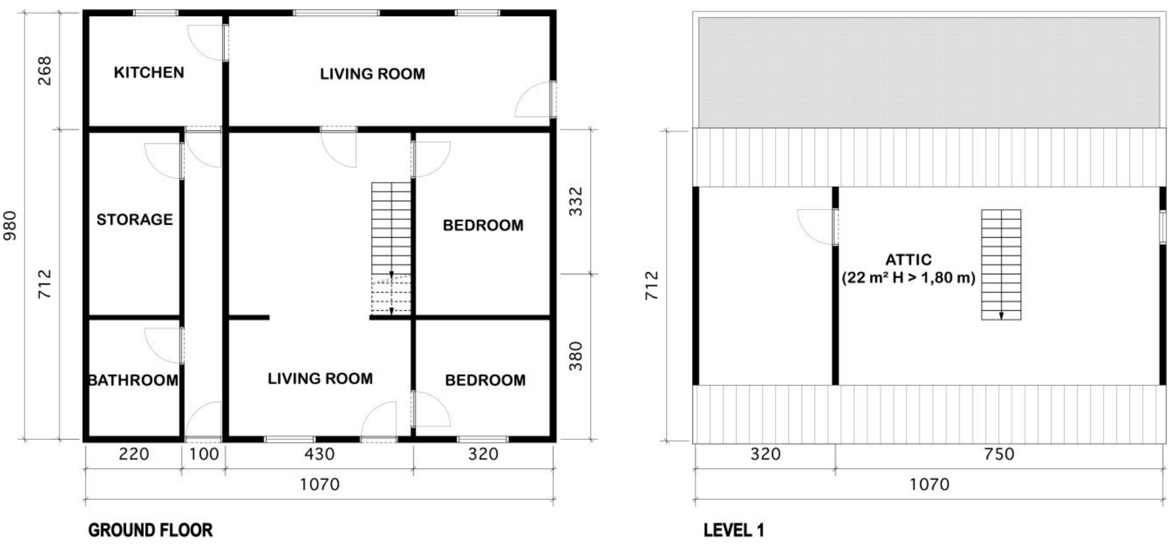


FIGURE 12 Floor plans of the detached dwelling, type 1 (Allacker 2010, 165)

The external and financial costs of all variants are plotted on a single graph (FIGURE 13).

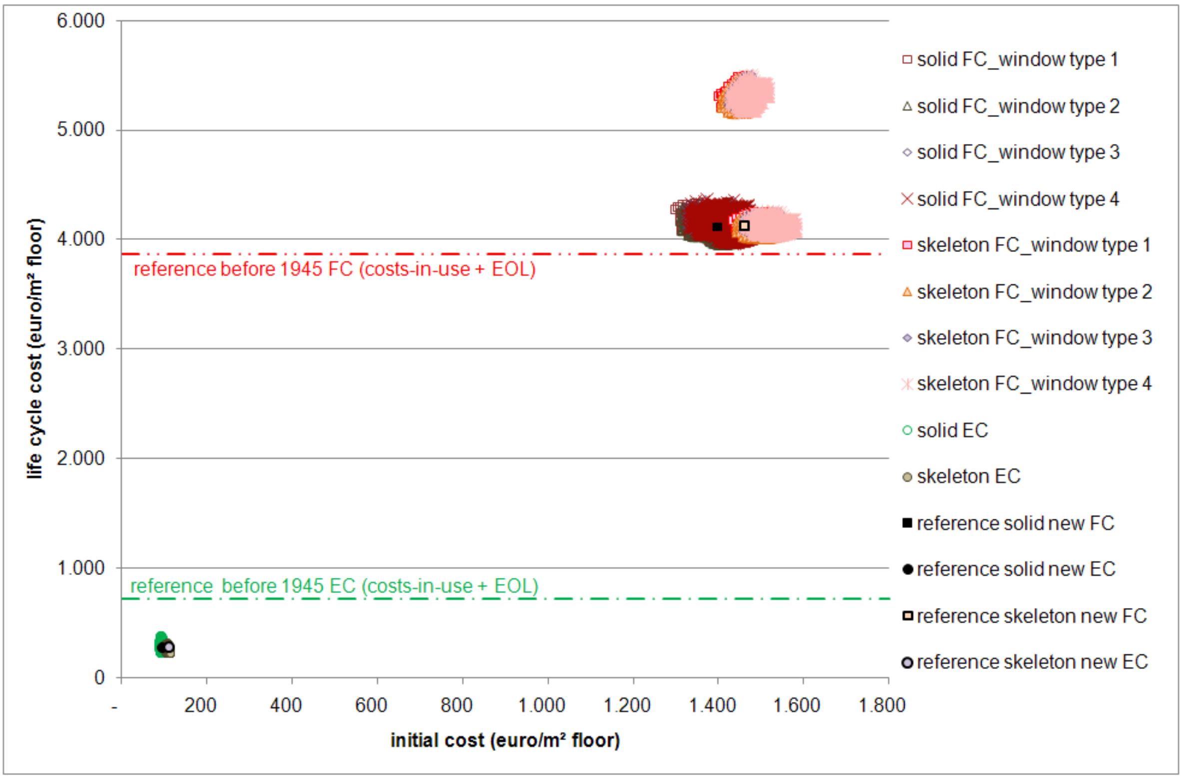


FIGURE 13 Detached, before 1945: initial versus lifecycle cost

The total costs are omitted to improve tangibility. The external cost represents on average 6% of the total cost, with a minimum of 4% and a maximum of 8%. The latter is thus mainly determined by the financial cost. For the dwelling representative of the period before 1945, the external cost of the 'remaining' cost represents 16% of the total cost (these costs are represented by a horizontal line on the graph).

The skeleton variants lead to a higher initial external, but approximately identical lifecycle external cost to the solid variants. The financial (initial and lifecycle) costs of the skeleton variants are higher than those of the solid variants.

Two clouds of results were found for the financial cost of the skeleton variants. The higher lifecycle costs proved to be the dwellings with outer walls with larch planks as external finishing. The high cost can be explained by the higher cleaning and maintenance cost compared to the brick veneer. The initial financial and total cost of the larch planks variants are slightly lower than those of the brick veneer variants. These are therefore situated on the financial and total cost Pareto front.

EXTERNAL COST

The external costs are shown separately in FIGURE 14. A distinction (different symbol) is made between the dwellings with another type of window.

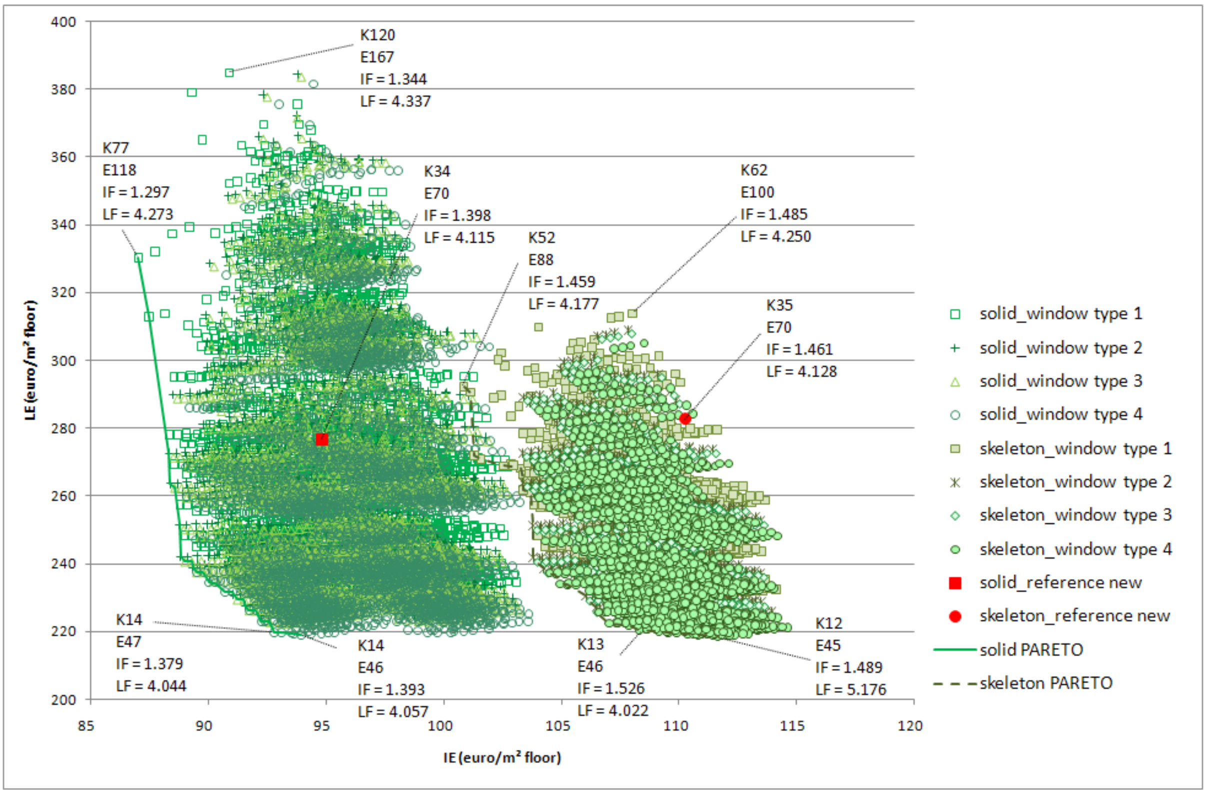


FIGURE 14 Detached, before 1945: initial versus lifecycle external cost.

The Pareto front is determined for the solid and skeleton variants separately. The 'remaining' cost for the reference for the period before 1945 is not indicated since its lifecycle external cost is much higher and would make the graph intangible. However, this cost is plotted on the graph in FIGURE 13.

The analysis reveals that for the solid variants, the dwellings with outer walls with stucco are preferred above the brick veneer variants. For the skeleton variants, the difference between the two external finishes is negligible. The Pareto front of the solid variants is shown in TABLE XIV which is equal to the Pareto front of all options.

From an environmental point of view, pitched roof insulation (8 cm rock wool) is the first priority. The subsequent priority is floor insulation (3 cm) combined with flat roof insulation (cellular concrete slab with 14 cm resol) and thermally improved glazing.

TABLE XIV Detached before 1945: Pareto options based on external cost for the solid alternatives.

	floor on grade	outer wall	flat roof	window	pitched roof	K	E	IE (€/m² floor)	LE (€/m² floor)
Pareto 1	GRFL0	OW8	FR0	VAR1	PR0	77	118	87,02	330,28
Pareto 2	GRFL0	OW8	FR0	VAR1	PR1	66	105	87,46	312,82
Pareto 3	GRFL1	OW8	FR3	VAR2	PR0	42	78	88,33	272,60
Pareto 4	GRFL2	OW8	FR3	VAR2	PR0	38	73	88,38	263,71
Pareto 5	*GRFL2*	*OW8*	*FR3*	*VAR3*	*PR0*	*37*	*72*	*88,54*	*262,39*
Pareto 6	GRFL1	OW8	FR3	VAR2	PR1	32	66	88,77	251,47
Pareto 7	GRFL2	OW8	FR3	VAR2	PR1	27	61	88,82	242,05
Pareto 8	GRFL2	OW8	FR3	VAR3	PR1	26	60	88,98	240,65
Pareto 9	*GRFL2*	*OW8*	*FR4*	*VAR3*	*PR1*	*26*	*60*	*89,28*	*240,60*
Pareto 10	GRFL3	OW8	FR3	VAR2	PR1	25	59	89,32	238,92
Pareto 11	GRFL3	OW8	FR3	VAR3	PR1	25	58	89,48	237,50
Pareto 12	*GRFL3*	*OW8*	*FR4*	*VAR3*	*PR1*	*24*	*58*	*89,78*	*237,45*
Pareto 13	GRFL3	OW8	FR3	VAR4	PR1	23	56	90,01	234,44
Pareto 14	*GRFL3*	*OW8*	*FR4*	*VAR4*	*PR1*	*23*	*56*	*90,31*	*234,38*
Pareto 15	GRFL3	OW9	FR3	VAR4	PR1	21	53	90,72	231,79
Pareto 16	*GRFL3*	*OW9*	*FR4*	*VAR4*	*PR1*	*20*	*53*	*91,03*	*231,70*
Pareto 17	GRFL2	OW8	FR3	VAR2	PR5	21	54	91,06	230,91
Pareto 18	GRFL2	OW8	FR3	VAR3	PR5	20	53	91,22	229,47
Pareto 19	*GRFL2*	*OW8*	*FR4*	*VAR3*	*PR5*	*20*	*53*	*91,51*	*229,40*
Pareto 20	GRFL3	OW8	FR3	VAR2	PR5	19	52	91,56	227,67
Pareto 21	GRFL3	OW8	FR3	VAR3	PR5	18	51	91,72	226,22
Pareto 22	*GRFL3*	*OW8*	*FR4*	*VAR3*	*PR5*	*18*	*51*	*92,01*	*226,14*
Pareto 23	GRFL3	OW8	FR3	VAR4	PR5	17	49	92,24	223,07
Pareto 24	GRFL3	OW8	FR4	VAR4	PR5	17	49	92,39	222,92
Pareto 25	*GRFL3*	*OW9*	*FR4*	*VAR3*	*PR5*	*16*	*48*	*92,59*	*222,86*
Pareto 26	**GRFL3**	**OW9**	**FR3**	**VAR4**	**PR5**	**14**	**47**	**92,81**	**219,78**
Pareto 27	GRFL3	OW9	FR4	VAR4	PR5	14	46	93,12	219,65
Pareto 28	GRFL3	OW9	FR3	VAR4	PR7	14	46	93,64	219,25
Pareto 29	GRFL3	OW9	FR4	VAR4	PR7	14	46	93,95	219,12

These first two steps are followed by increased floor insulation (10 cm), opting for insulated window frames, increased floor insulation (21 cm), triple glazing, increased outer wall insulation (stucco on 20 cm EPS) and increased pitched roof insulation (30 cm). These measures lead to the sub-optimum, characterised by K14 and E47.

The first Pareto optimum (option with the lowest IE) corresponds to K77 and E118. This option requires an initial financial investment cost of 1.297 euro/m² floor and results in a financial lifecycle cost of 4.273 euro/m² floor. Compared to the first Pareto optimum, a reduction in the LE of 33% is achieved by the sub-optimum (Pareto 26). This option requires an extra financial investment of 82 euro/m² floor (6%), while the lifecycle financial cost is reduced by 5,4%.

Pareto 26 consists of a floor on grade with 21 cm PUR, OW9 (stucco on 20 cm EPS), FR3 (cellular concrete slab with 14 cm resol), PR5 (rafters + purlins with 30 cm rock wool) and triple glazing with thermally insulated wood frames.

Several of the Pareto steps should not be taken to reach to the sub-optimum since these require a high extra investment for a small reduction in the lifecycle cost (FIGURE 14). It concerns Pareto 5, 9, 12, 14, 16, 19, 22 and 25 (italics in TABLE XIV).

The absolute optimum is characterised by K14 and E46. Compared to the first Pareto optimum, a reduction of 34% in the LE is achieved (1 % more than for the sub-optimum). This option however requires an extra financial investment of 96 euro/m² floor (increase of 7%, and thus 1% more than for the sub-optimum), while the lifecycle financial cost is reduced by 5% (slightly higher LF than for the sub-optimum). The environmental investment thus also results in a lifecycle financial improvement. However, it requires a 7% extra financial investment.

The option with the highest lifecycle external cost of all analysed options equals K120 and E167. In comparison to this dwelling, the sub-optimum (Pareto 26) leads to a reduction of 43% in the LE and 7% in the LF. Compared to the dwelling representative of the period before 1945, the LE of the sub-optimum is lower than one third of its ‘remaining’ cost, while the LF is 5% higher.

An identical analysis of the skeleton variants reveals that conclusions are similar. The first Pareto option (lowest IE) is characterised by K52 and E88. The absolute optimum equals K12 and E45. This optimisation leads to a 25% reduction in LE, requiring an extra financial investment of 30 euro/m² floor (2%). It results in an increase in the lifecycle financial cost of 24%.

The sub-optimum (as indicated on the graph in FIGURE 14) still leads to a reduction in the external lifecycle cost of 25%. Although, the extra financial investment increases to 76 euro/m² floor (or thus an extra required investment of 5%), it results in a reduction in the lifecycle financial cost of 4%. The reduction in the lifecycle external cost does not always imply a reduction in the lifecycle financial cost. An analysis of both is thus required to enable correct decisions. Considering the total cost is another option for evaluating both. The skeleton variant with the highest lifecycle external cost of all analysed options is characterised by K62 and E100. Compared to this option, a reduction in the lifecycle external cost of 30% is achieved by the sub-optimum. This requires an extra financial investment of 40 euro/m² floor (3%), but results in a reduction in the lifecycle financial cost of 5%.

FINANCIAL AND TOTAL COST

The financial cost Pareto set differs from the one based on external cost (TABLE XV).

TABLE XV Detached before 1945: Pareto options based on financial cost for the solid alternatives

	floor on grade	outer wall	flat roof	window	pitched roof	K	E	IF (€/m² floor)	LF (€/m² floor)
Pareto 1	GRFL0	OW8	FR0	VAR1	PR0	77	118	1.297,10	4.273,26
Pareto 2	GRFL3	OW8	FR0	VAR2	PR0	58	96	1.309,98	4.162,87
Pareto 3	GRFL3	OW8	FR1	VAR2	PR0	37	72	1.313,05	4.076,42
Pareto 4	*GRFL3*	*OW8*	*FR3*	*VAR2*	*PR0*	*36*	*71*	*1.315,76*	*4.073,53*
Pareto 5	GRFL3	OW8	FR1	VAR2	PR1	26	59	1.327,68	4.034,33
Pareto 6	GRFL3	OW8	FR3	VAR2	PR1	25	59	1.330,40	4.031,28
Pareto 7	GRFL3	OW8	FR1	VAR2	PR10	22	56	1.337,38	4.025,17
Pareto 8	GRFL3	OW8	FR1	VAR2	PR11	22	55	1.339,55	4.022,74
Pareto 9	GRFL3	OW8	FR3	VAR2	PR10	22	55	1.340,10	4.022,08
Pareto 10	GRFL3	OW8	FR3	VAR2	PR11	21	54	1.342,27	4.019,60
Pareto 11	*GRFL3*	*OW8*	*FR3*	*VAR2*	*PR5*	*19*	*52*	*1.350,42*	*4.017,95*
Pareto 12	*GRFL3*	*OW1*	*FR3*	*VAR2*	*PR0*	*41*	*76*	*1.366,50*	*4.016,58*
Pareto 13	*GRFL3*	*OW2*	*FR1*	*VAR2*	*PR0*	*36*	*71*	*1.371,64*	*4.006,63*
Pareto 14	*GRFL3*	*OW2*	*FR3*	*VAR2*	*PR0*	*36*	*70*	*1.373,69*	*4.004,43*
Pareto 15	*GRFL3*	*OW1*	*FR1*	*VAR1*	*PR1*	*35*	*68*	*1.377,90*	*3.990,10*
Pareto 16	*GRFL3*	*OW1*	*FR1*	*VAR2*	*PR1*	*31*	*65*	*1.378,95*	*3.977,38*
Pareto 17	GRFL3	OW1	FR3	VAR2	PR1	30	64	1.381,11	3.975,27
Pareto 18	GRFL3	OW2	FR1	VAR2	PR1	25	59	1.386,18	3.961,90
Pareto 19	GRFL3	OW2	FR3	VAR2	PR1	25	58	1.388,23	3.959,54
Pareto 20	*GRFL3*	*OW2*	*FR1*	*VAR2*	*PR9*	*24*	*57*	*1.393,78*	*3.958,81*
Pareto 21	*GRFL3*	*OW2*	*FR3*	*VAR2*	*PR9*	*23*	*56*	*1.395,83*	*3.956,42*
Pareto 22	GRFL3	OW2	FR1	VAR2	PR10	22	55	1.395,85	3.951,85
Pareto 23	GRFL3	OW2	FR3	VAR2	PR10	21	54	1.397,90	3.949,44
Pareto 24	**GRFL3**	**OW2**	**FR1**	**VAR2**	**PR11**	**21**	**54**	**1.398,01**	**3.949,20**
Pareto 25	GRFL3	OW2	FR3	VAR2	PR11	20	53	1.400,07	3.946,75
Pareto 26	GRFL3	OW3	FR3	VAR2	PR11	18	50	1.407,86	3.945,41
Pareto 27	GRFL3	OW2	FR3	VAR2	PR5	19	51	1.408,20	3.944,59
Pareto 28	GRFL3	OW3	FR3	VAR2	PR5	16	48	1.415,98	3.942,76

The financial cost sub-optimum (Pareto 24) corresponds to a dwelling consisting of a floor on grade with the highest considered insulation level, outer wall 2 (cavity wall, 14 cm rock wool with a brick veneer), pitched roof 11 (closely placed rafters foreseen of 18 cm rock wool) and thermally improved glazing with standard window frames. This sub-optimum corresponds to K21 and E54.

A similar analysis is executed for the total cost (TABLE XVI). Again 28 Pareto optima are identified. These correspond to a large extent to the optima based on financial cost. However, differences are noticed. Inclusion of the external costs would therefore influence the decisions.

The absolute optimum based on total cost corresponds to the one based on financial cost, while the sub-optima differ.

TABLE XVI Detached before 1945: Pareto options based on total cost for the solid alternatives.

	floor on grade	outer wall	flat roof	window	pitched roof	K	E	IT (€/m² floor)	LT (€/m² floor)
Pareto 1	GRFL0	OW8	FR0	VAR1	PR0	77	118	1.384,13	4.603,54
Pareto 2	*GRFL0*	*OW8*	*FR0*	*VAR1*	*PR1*	*66*	*105*	*1.399,20*	*4.554,61*
Pareto 3	*GRFL2*	*OW8*	*FR0*	*VAR2*	*PR0*	*59*	*98*	*1.400,04*	*4.500,30*
Pareto 4	*GRFL3*	*OW8*	*FR0*	*VAR2*	*PR0*	*58*	*96*	*1.400,42*	*4.465,72*
Pareto 5	*GRFL2*	*OW8*	*FR1*	*VAR1*	*PR0*	*42*	*77*	*1.403,57*	*4.395,76*
Pareto 6	GRFL3	OW8	FR1	VAR2	PR0	37	72	1.403,66	4.340,30
Pareto 7	GRFL3	OW8	FR3	VAR2	PR0	36	71	1.404,65	4.334,31
Pareto 8	*GRFL2*	*OW8*	*FR1*	*VAR1*	*PR1*	*32*	*65*	*1.418,64*	*4.334,30*
Pareto 9	GRFL3	OW8	FR1	VAR2	PR1	26	59	1.418,73	4.276,40
Pareto 10	GRFL3	OW8	FR3	VAR2	PR1	25	59	1.419,72	4.270,20
Pareto 11	*GRFL3*	*OW8*	*FR3*	*VAR2*	*PR9*	*23*	*57*	*1.429,01*	*4.264,36*
Pareto 12	*GRFL3*	*OW8*	*FR1*	*VAR2*	*PR10*	*22*	*56*	*1.430,48*	*4.261,00*
Pareto 13	GRFL3	OW8	FR3	VAR2	PR10	22	55	1.431,48	4.254,74
Pareto 14	GRFL3	OW8	FR3	VAR2	PR11	21	54	1.434,04	4.250,79
Pareto 15	GRFL3	OW8	FR3	VAR2	PR5	19	52	1.441,98	4.245,62
Pareto 16	*GRFL3*	*OW1*	*FR3*	*VAR1*	*PR1*	*34*	*68*	*1.472,82*	*4.242,20*
Pareto 17	GRFL3	OW1	FR1	VAR2	PR1	31	65	1.473,43	4.228,64
Pareto 18	GRFL3	OW1	FR3	VAR2	PR1	30	64	1.473,83	4.223,37
Pareto 19	GRFL3	OW2	FR1	VAR2	PR1	25	59	1.482,22	4.205,23
Pareto 20	GRFL3	OW2	FR3	VAR2	PR1	25	58	1.482,49	4.199,63
Pareto 21	*GRFL3*	*OW2*	*FR1*	*VAR2*	*PR9*	*24*	*57*	*1.491,48*	*4.198,76*
Pareto 22	*GRFL3*	*OW2*	*FR3*	*VAR2*	*PR9*	*23*	*56*	*1.491,75*	*4.193,13*
Pareto 23	*GRFL3*	*OW2*	*FR1*	*VAR2*	*PR10*	*22*	*55*	*1.493,94*	*4.188,59*
Pareto 24	GRFL3	OW2	FR3	VAR2	PR10	21	54	1.494,21	4.182,92
Pareto 25	GRFL3	OW2	FR3	VAR2	PR11	20	53	1.496,77	4.178,67
Pareto 26	*GRFL3*	*OW2*	*FR1*	*VAR2*	*PR5*	*19*	*52*	*1.504,41*	*4.178,52*
Pareto 27	**GRFL3**	**OW2**	**FR3**	**VAR2**	**PR5**	**19**	**51**	**1.504,68**	**4.172,81**
Pareto 28	GRFL3	OW3	FR3	VAR2	PR5	16	48	1.513,92	4.167,97

The total cost sub-optimum (Pareto 27 in TABLE XVI) corresponds to K19 and E51. It consists of a well insulated floor on grade (21 cm PUR), outer wall 2 (cavity with 14 cm rock wool and a brick veneer), flat roof FR3 (cellular concrete slab with 14 cm resol), pitched roof PR5 (30 cm rock wool) and thermally improved glazing with standard window frames.

CONTRIBUTION PHASES

In FIGURE 15 the contribution of the financial and external costs during the different lifecycle phases and processes of the dwelling are presented for a selection of alternatives. The selection includes the reference dwellings (REF), the solid and skeleton sub-optima (OPTIM) based on financial, external and total cost and the solid and skeleton absolute optima (MIN) based on external cost. For the existing dwelling, a fictitious initial cost is considered at the current prices in order to gain insight into the contribution of the initial cost to the other costs compared to the more recent dwellings.

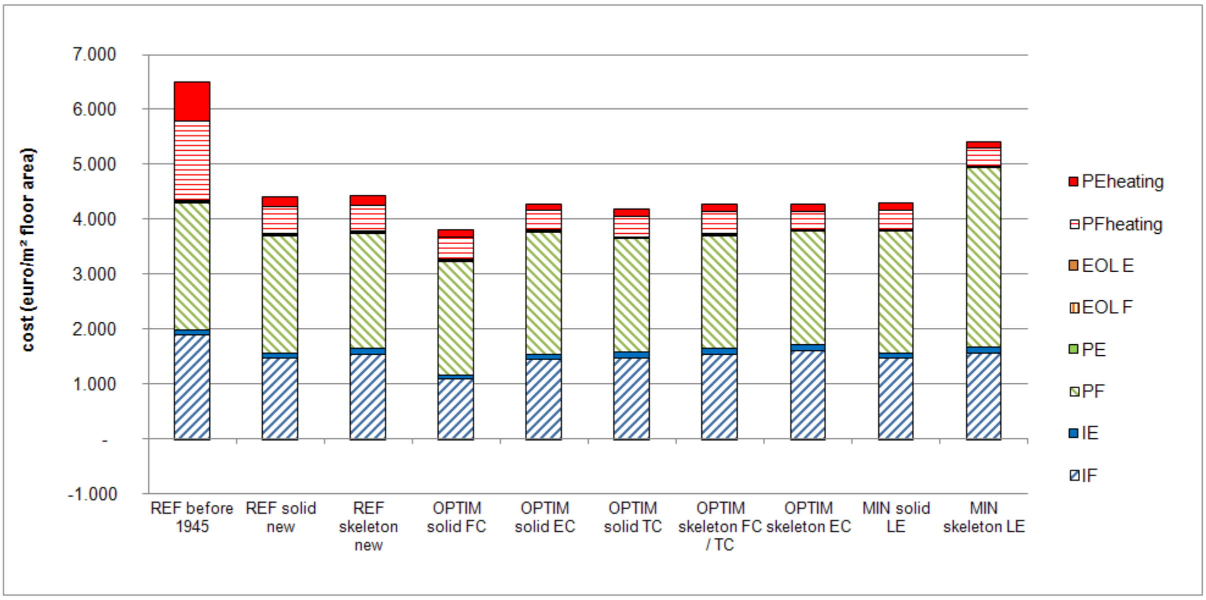


FIGURE 15 Detached, before 1945: financial and external costs for the different phases and processes for a selection of variants.

The importance of the financial cost in the total cost is confirmed from this graph. Furthermore, the difference between the financial and external costs becomes clear. While for the financial cost the periodic costs are the most important, followed by the investment cost, the heating cost is most important from an environmental point of view. The optimisation potential from an environmental perspective is therefore mainly the reduction in the energy use, while from a financial point of view optimisation of cleaning, maintenance and replacement costs should be focussed on.

A more detailed analysis of the external cost is presented in FIGURE 16 and FIGURE 17 FIGURE 16 includes the reference dwellings, the solid and skeleton sub-optima based on external cost, the solid and skeleton absolute optima based on lifecycle external cost and three extra optimisation variants of the solid sub-optimum. The extra optimisation is based on the results of the element analysis and includes the choice for laminate instead of ceramic tiles for the floor on grade, the use of perforated clay bricks instead of building clay bricks for the outer walls and sand-lime brick for the load bearing inner walls, cellulose instead of rock wool for the pitched roof and the use of a wood wool board instead of a cement fibre board as underlay. This extra option is analysed for an air-tightness of 6 (unchanged), 3 and 0,6 air changes per hour.

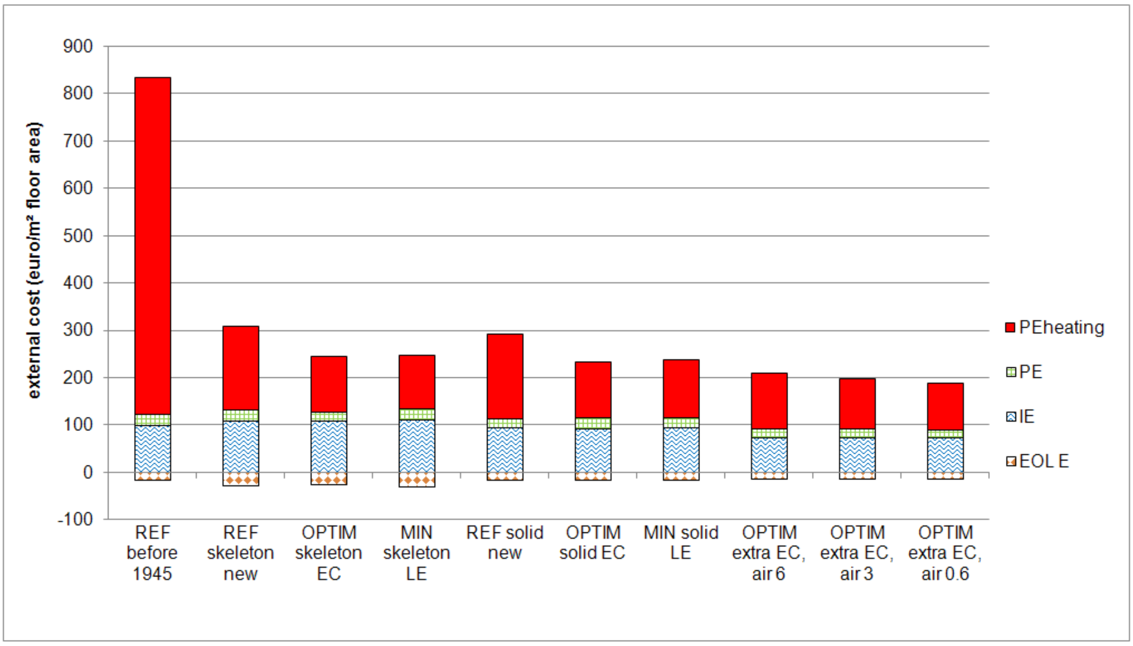


FIGURE 16 Detached, before 1945: external costs for the different phases and processes for a selection of variants.

In FIGURE 17 three variants are summarised:

- Reference before 1945
- Pareto sub-optimum based on external cost
- Extra optimisation of the environmental cost sub-optimum based on the element analysis and for improved air-tightness (0,6 air changes per hour).

The analysis reveals that the lifecycle environmental cost of the existing dwelling is mainly determined by the heating cost. The solid variants induce a lower initial environmental cost than the skeleton variants.

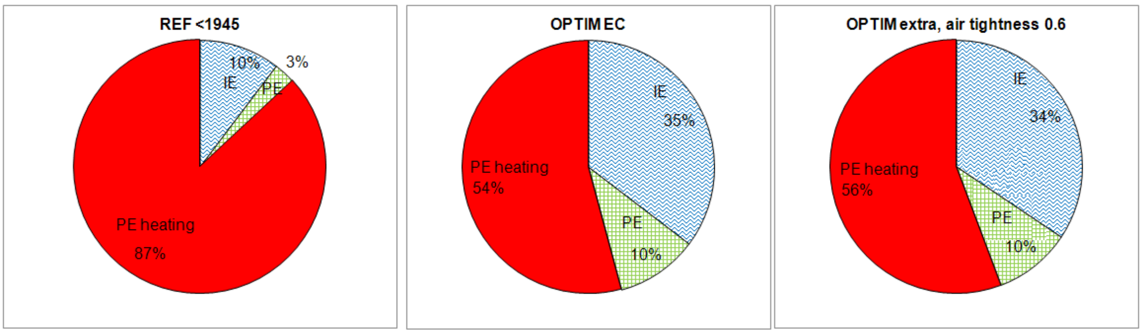


FIGURE 17 Detached, before 1945: proportional distribution of the external costs for the different phases and processes for a selection of variants.

The skeleton sub-optimum leads to a 22% reduction in the LE compared to common practice to date (REF skeleton new). A 20,5% reduction in the LE is noticed for the solid sub-optimum compared to common (solid) practice (REF new solid). The lifecycle external cost of the extra optimal variant with improved air-tightness (last in FIGURE 16) is 21% lower than of the earlier defined sub-optimum (6th in FIGURE 16). The net energy demand equals 44,5 kWh/m^2, year which is higher than the maximum allowed for the passive standard (15 kWh/m^2, year).

FIGURE 17 reveals that for the older dwelling, heating represents 87% of the lifecycle cost while the construction of the dwelling is responsible for 10%. The construction cost gains importance for the optimised variants to 35% for the solid sub-optimum and to 34% for the extra optimum with improved air-tightness.

CONTRIBUTION ELEMENTS

For the extra optimum (based on environmental cost), the contribution of the different elements in the lifecycle financial and external cost (excluding heating) is investigated and presented in FIGURE 18. From a financial point of view, the elements contributing most are the floor on grade and the outer walls. The elements which contribute most to the environmental cost are the floor on grade, the outer walls and the intermediate floors. The elements which are not mentioned represent less than 10% of the lifecycle cost.

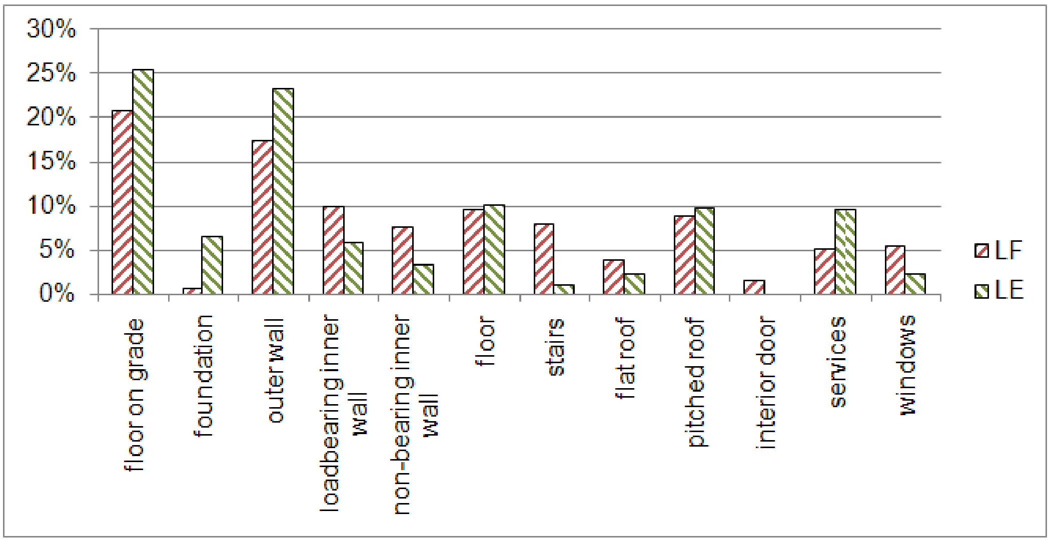


FIGURE 18 Detached, before 1945: contribution of the different elements to the lifecycle financial and external cost (excluding heating) for the extra environmental optimum.

SENSITIVITY ANALYSIS

The sensitivity analysis reveals that the results are influenced by the considered life span of the dwelling. It is mainly the importance of the heating demand which plays a role. Therefore the obtained K and E values of the optima (first Pareto option, sub-optimum and absolute optimum) are summarised for the three considered life spans (30, 60 and 120 years) in TABLE XVII. For a reduced life span of 30 years the optimal K and E values are higher, while for a prolonged life span (120 years) the optimal values are approximately identical based on the environmental cost optimisation, but lower based on the financial and total cost optimisation. The first Pareto option is identical for all scenarios.

TABLE XVII Detached, before 1945: summary of the K and E values of the optima (IE/LE, IF/LF and IT/LT) for the three considered dwelling life spans (30, 60 and 120 years)

	30 year						60 year						120 year					
	IE/LE		IF/LF		IT/LT		IE/LE		IF/LF		IT/LT		IE/LE		IF/LF		IT/LT	
optima																		
first	K77	E118	K77	E118	K77	E118	K77	E118	K77	E118	K77	E118	K77	E118	K77	E118	K77	E118
sub	K27	E61	K37	E72	K25	E60	K14	E47	K21	E54	K19	E51	K14	E46	K16	E48	K16	E48
absolute	K14	E47	K25	E59	K21	E54	K14	E46	K16	E48	K16	E48	K13	E45	K16	E48	K14	E45

Changing the economic parameters to a higher growth rate for the financial energy prices (4%) and for the external material costs (0,5%) does not lead to other decisions. For an increased financial and external cost discount rate (4% and 3% respectively), the Pareto front does change. For the external cost the difference is minor. The absolute optimum based on external cost equals the last-but-one (Pareto 28) according to the basic scenario. For the financial and total cost, the absolute optimum equals Pareto 26 in TABLE XV, which means a K and E-value which are 2 points higher (K18 and E50). However, the latter is still situated in the horizontal slope of the Pareto front according to the basic scenario and was therefore already questioned. The sub-optima remain unchanged.

General conclusions based on the 16 case studies

Similar to the above assessment of the detached dwelling, all 16 case studies were analysed and reported. In the subsequent paragraphs, the most important findings based on the sixteen case studies are summarised.

i. Influence of internalisation of external costs on final decisions?

   The contribution of the initial external cost was on average limited to 6% of the initial total cost and the contribution of the lifecycle external cost to 5% on average of the lifecycle total cost. In consequence, although internalisation would have an impact on decisions, it would not influence the final decisions to a great extent.

On the other hand, internalisation would not lead to unaffordable housing, except for dwellings with a high energy demand. To move towards a more sustainable dwelling stock, it therefore seems important to evaluate financial and environmental external costs separately.

ii. What are the priorities to reduce the environmental external cost?

Based on the analysis of the 16 cases as described in the previous section and in addition a more roughly estimation of the costs due to electricity use for appliances and lighting, fresh water use and transport of the inhabitants, following priorities were identified. The transport of the inhabitants leads to the highest environmental and financial cost. The location of newly built dwellings and re-location of demolished dwellings therefore is of primary importance to move towards a more sustainable building stock. Moreover, the transport impact can be further reduced by discouraging the use of private cars and encouraging and further developing public transport. Beside transport, heating and electricity use contribute most to the lifecycle external cost of dwellings according to common practice to date. These are followed by the initial phase (production, transport to the construction site and material losses during construction) and finally by fresh water use. For the optimised dwellings, either the initial phase or heating contribute most to the lifecycle external cost, followed by the electricity and fresh water use. Beside transport, heating contributes most to the lifecycle environmental external cost of the dwellings built before 1990.

For an efficient reduction in lifecycle external cost, the location, choice of building characteristics, insulation level, air tightness and choice of technical systems were proved to be the order of priority. Important building characteristics are size of the dwelling, thermal compactness, glazed area and orientation. For the increase in insulation level one should focus on the complete building skin. The optimal insulation thicknesses as determined through the assessment at the element level should be strived for. However, if a limited budget is available, actions in order of priority can be defined. These depend on the efficiency of the cost reduction of each element, the ratios of the elements and the available budget. In addition, it is important to take into account the (im)possibility of improvements later on in the lifecycle. If, for example, the insulation of the floor on grade is identified as last priority but it is impossible to increase the insulation level of the floor on grade at reasonable costs later on, the floor insulation should be the first priority.

iii. Priorities and optima identical from a financial and environmental perspective?

The financial cost analysis revealed that for both the existing dwellings and dwellings according to common practice to date, cleaning, maintenance and replacements contribute most to the lifecycle financial cost (considering a life span of the dwelling of 60 years). For the optimised dwelling variants, these are approximately evenly important to the initial cost. In contradiction to the environmental external costs, the heating cost only contributes to a minor extent to the lifecycle financial cost. Consequently, both the priorities and optima based on financial and environmental external costs differ. From an environmental perspective the dwellings should be insulated better than would be done solely based on financial costs. In consequence the optimal dwellings based on environmental external costs are characterised by a lower net energy demand than the optima based on financial costs. However, the measures concerning the energy reduction of dwellings (insulation and air tightness) based on lifecycle financial costs are already an important step forward considered to these based on investments costs only. The latter is sadly enough often the most important decision criteria to date. Despite this observation, not all measures based on lifecycle financial costs are in line with those based on lifecycle environmental costs. One example is the cheaper blue stone from Asia inducing an important extra environmental external cost compared to blue stone from Belgium.

iv. Priorities from an environmental perspective, financially affordable and justifiable?

The above described contradiction between financial and environmental external costs implies that measures which lead to a reduction in lifecycle external cost do not always imply a reduction in the lifecycle financial cost. The environmental optimisation based on energy-related measures resulted for ten of the sixteen dwellings in a reduction in the lifecycle financial cost with an average reduction of 4% and a maximum of 16%. The majority of these measures were thus justifiable from a financial lifecycle cost perspective. Despite this observation, it is important to evaluate all measures carefully because some of the environmental optima resulted in an increase in the lifecycle financial cost.

The affordability of the environmental optima (of energy-related measures) on the other hand was positively confirmed by observing an average increase of financial investment cost of 6%. If this is not affordable for the private dwelling owner, it certainly is through means of support from the government.

Straightforward conclusions could not be drawn for the non-energy related measures (e.g. material choice, choice of technical services). The above example of blue stone from Asia and Belgium illustrates this finding. Each single measure thus requires an assessment based on financial and environmental external cost.

v. Environmental optimisation potential

The environmental optimisation potential of the dwellings compared to common practice to date is on average 36%, with a minimum of 30% and a maximum of 55%. These percentages were based on measures related to the choice of building materials and technical services, insulation level and air-tightness of the dwellings. Comparison of the dwellings moreover revealed a further optimisation potential through measures related to the building characteristics (e.g. layout, size, window area, orientation). This finding is based on a comparison of the different dwelling types revealing that the lifecycle cost of the dwelling with the highest lifecycle cost was about 60% higher than the lifecycle cost of the dwelling with the lowest lifecycle cost. (Allacker 2010, 413)

vi. Preference dwelling type

There was no absolute preference identified between the dwelling types. The financial and environmental external costs depend on a combination of characteristics such as dwelling type and size, thermal compactness, window area, insulation value and material choice. Despite this lack of absolute preference, it was observed that the net heating demand of the optimised dwelling variant was lowest for the terraced house (on average 15 kWh/m² floor per year) and highest for the detached house (on average 39 kWh/m² floor per year).

vii. Low-energy and passive standard as optimum?

The evaluation of the low-energy or passive standard as optimum was limited to the restrictions on heating demand. Low-energy dwellings are in that sense defined as dwellings with a maximum yearly net heating demand of 30 kWh/m² floor area (VEA 2010). Passive houses are defined as dwellings with a maximum yearly net heating demand of 15 kWh/m² floor area (PHPP 2010).

The yearly net heating demand of the financial optimum of two of the sixteen cases was between 15 and 30 kWh/m² floor and only one reached the passive standard. Based on the environmental external cost optimisation, eight dwellings were characterised by a net heating demand between 15 and 30 kWh/m² floor and only two reached the passive standard. It should however be stressed that the analysis did not focus on dwellings which were designed as low-energy or passive houses.

The low-energy or passive standard may be the optimum for dwellings with an adapted design, layout, glazing area and orientation. However, based on the results it is clear that an adaptation of current building practice and layout prescriptions is necessary, if not a prerequisite, to develop low-energy and passive houses in an efficient way. (Allacker and De Troyer 2011)

viii. Assessment at the dwelling level compared to the building element level

In general, the optima determined at the dwelling level are composed of building element options which coincide with the earlier defined optima at the element level. If there are no investment budget restrictions, the order of priority of the measures can be investigated at the element level. However, the order of priority of measures in case of an increasing initial budget differs for each dwelling based on the element ratios. Therefore, if there is a limited budget available the assessment at the element level should be linked to the building level. Moreover, several aspects can only be assessed at the building level, such as orientation, choice of windows (e.g. solar gains), geometric characteristics, air-tightness, ventilation and technical services for heating. The element analysis can thus be seen as an important but more limited step in the optimisation procedure.

ix. Quality assessment as decision parameter

Although not elaborated in this final report, the quality of the sixteen analysed dwellings was evaluated in order to enable a comparison of their costs in relation to their quality. The inclusion of the quality evaluation confirmed the hypothesis that dwellings with a higher cost (financial and/or environmental) may be preferred because their quality is more appreciated. This is not experienced as problematic, as long as the dwelling owner/renter is willing to pay for the extra costs (financial and environmental). Moreover, it is obvious that quality is differently experienced - and thus that a certain dwelling is differently appreciated - by different persons or at different moments during one's lifetime. The question rises if people should not be encouraged more to leave the house they bought/built when they were starting their family once the children leave the house. The original house is then presumably much too big for this two-person family. In order to allow such more dynamic life style, a divergence in dwelling stock is important and should include small dwellings/apartments with a high quality appreciated by this category of people in our society.

x. Importance of the choice of functional unit

By changing the functional unit from 1 m² floor area to 1 inhabitant it was clear that the dwelling preference changed.

The number of square meters per inhabitant, or more general the volume per inhabitant, is an important parameter to reduce the environmental impact and costs. Space however is a strongly appreciated quality of buildings and it is therefore important to create smaller dwellings with a great feeling of space in order to convince people to live in smaller dwellings. On the other hand, larger buildings/rooms are often characterised by a higher degree of flexibility and might therefore result in a longer service life span. A balance between size and flexibility therefore seems the most recommended way to reach for sustainable housing.

Outputs:

i. Internal research reports

- Tomasetig, B., Spirinckx, C., Allacker, K and Putzeys, K. (2008). Note on selection of extreme types, BELSPO, 75 pages.
- Putzeys, K., Vekemans, G., Spirinckx, C. and Allacker, K. (2008). Interim note on extreme cases, BELSPO, 69 pages.
- Allacker, K., De Troyer, F., Putzeys, K., Vekemans, G. and Spirinckx, C. (2008). Final note on extreme cases, BELSPO, 139 pages.
- Janssen, A., Putzeys, K., Allacker, K. and De Troyer, F. (2008). Note on selection of representative dwelling types, BELSPO, 41 pages.
- Allacker, K., De Troyer, F., Janssen, A. and Debacker, W. (2010). Final note on representative cases, BELSPO, 203 pages.

ii. PhD dissertation:

Allacker, K. (2010). Sustainable building: The development of an evaluation method. Doctoral dissertation, Katholieke Universiteit Leuven, Leuven, Belgium.

iii. Other publications: see section 6

d. Assessment of renovation measures

Based on the finding that the heating costs of the existing dwellings were very important, energy-saving measures were focused on. For the two case studies, four building elements were renovated, i.e. exterior walls, inclined (terraced dwelling) or flat (detached dwelling) roof, windows and technical installations. The floor on grade was not considered, because renovation was too expensive (no cellar).

Terraced dwelling, type 1 (period before 1945)

The dwelling consists of a ground floor, a first floor and an attic under inclined roof. An overview of the four refurbished building elements with their reference composition and the applied renovation measures is given in TABLE XVIII. In total, 295 dwelling variants were analysed, distinguishing between the non-renovated dwellings (reference dwelling, with and without underlay), renovated dwellings with a selective renovation (only one, two or three of the building elements were renovated) and dwellings with complete renovation (all four building elements were refurbished).

TABLE XVIIIa Terraced dwelling, type 1 (period before 1945): overview of the reference composition and the different renovation measures (part A)

Building element	Reference composition	Renovation measures
exterior wall	• brick 30 cm • gypsum plaster • paint	• ***stucco on insulation*** (front facade + back facade): o EPS: 6 cm, 10 cm, 14 cm, 18 cm, 10 (front) +14 (back) cm, 10 (front)+18 (back) cm • ***internal insulation between wooden battens + gypsum board (+ acrylic paint) + stucco on brickwork*** (front facade) o rock wool: 6 cm, 9 cm, 14 cm o partial demolition of interior wall (thermal break) **combined with *stucco on insulation*** (back facade): o EPS insulation: 6 cm, 10 cm, 14 cm
windows	• old wooden frame • single glazing 6 mm • aluminium or steel spacer	• ***new standard wooden windows with thermally improved double glazing***: o replacement of old window frame by standard wooden frame o replacement of single glazing by thermally improved double glazing o thermally improved spacer • ***new standard wooden windows with triple glazing***: o replacement of old window frame by standard wooden frame o replacement of single glazing by triple glazing o thermally improved spacer
inclined roof	• ***reference*** (roof without underlay): o purlins o arrises o tile laths o ceramic roof tiles • ***variant on reference*** (roof with underlay): o purlins o arrises o wood-fibre board o counter battens o tile laths o ceramic roof tiles	• ***thermal insulation + external and internal finishing*** (renovation of reference): o rock wool between existing arrises (7.5 cm) o rock wool between existing purlins, including extra wooden battens if necessary (no insulation, 10 cm, 18 cm, 22 cm) o rock wool insulation under existing purlins, including extra wooden battens if necessary (no insulation, 8 cm) o wood-fibre board o counter battens o replacement of existing tile laths o replacement of existing ceramic roof tiles o vapour barrier o gypsum board on wooden battens • ***thermal insulation + internal finishing*** (renovation of reference variant): o rock wool between existing arrises (7.5 cm) o rock wool between existing purlins, including extra wooden battens if necessary (no insulation, 10 cm, 18 cm, 22 cm) o rock wool under existing purlins, including extra wooden battens if necessary (no insulation, 8 cm) o vapour barrier o gypsum board on wooden battens

TABLE XVIIIb Terraced dwelling, type 1 (period before 1945): overview of the reference composition and the different renovation measures (part B)

Building element	Reference composition	Renovation measures
technical installations	• non-condensing oil boiler • oil storage tank 3300 l • cast iron radiators • manual valves and room thermostat • separate hot water storage vessel 120 l • no ventilation system	• ***replacement of existing heating and hot water installation and new ventilation system***: ○ condensing gas boiler, combi, instant ○ standard panel radiators ○ thermostatic valves and outside temperature sensor ○ ventilation unit system C, including ducts and internal grids ○ removal of oil storage tank

FINANCIAL COST

In FIGURE 19, the initial (IF) and lifecycle (LF) financial costs of all renovated dwellings are compared to the remaining financial cost of the non-refurbished dwelling (green dot at IF = 0 €).

Most of the renovated dwellings were characterised by a lower lifecycle financial cost than the remaining cost of the non-refurbished dwelling. This means that the investment costs of the refurbishing measures were compensated by a reduction in costs-in-use over a time period of 60 years.

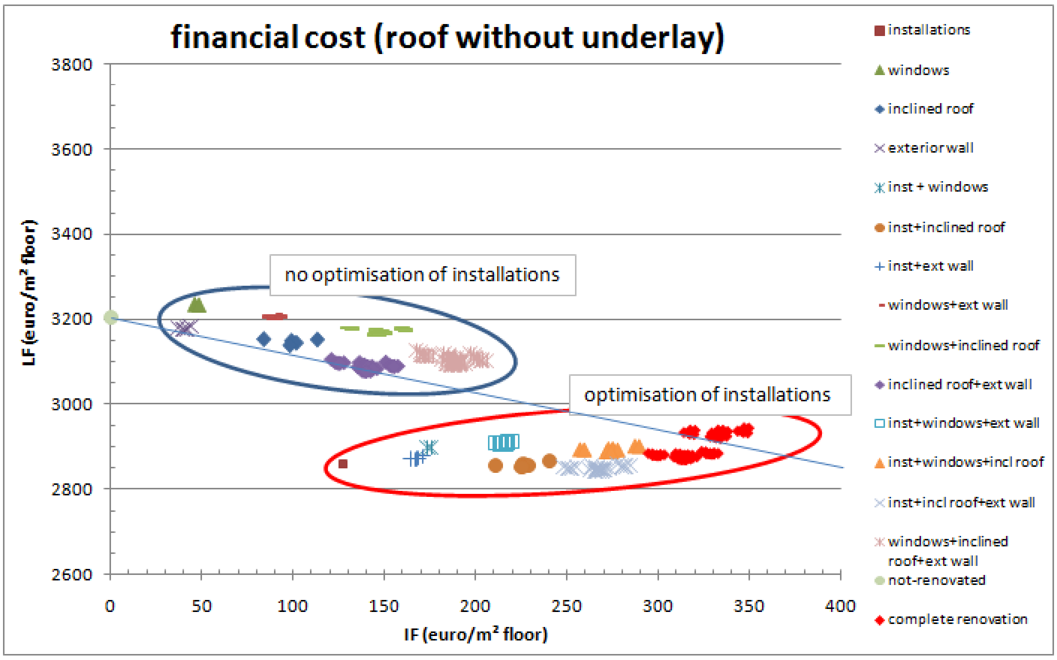


FIGURE 19 Terraced dwelling, type 1 (period before 1945): initial (IF) and lifecycle (LF) financial costs for all renovation variants, including the non-renovated reference dwelling (roof without underlay) (service life: 60 years)

Only two of the renovation measures led to a higher lifecycle cost, i.e. replacement of windows and replacement of windows in combination with exterior wall insulation. The higher LF costs for these measures were due to the higher initial, periodic (replacement) and EOL costs for wooden window frames with double or triple glazing and the fact that the reduction in solar gains overruled the reduced heat losses.

The individual refurbishment measure, leading to the largest reduction in lifecycle financial costs for the smallest increase in investment cost, consisted of replacing the heating and hot water installations by a combi condensing gas boiler and installing a ventilation system C. The decrease in LF was mainly due to the lower replacement cost and the higher efficiency of a condensing gas boiler compared to the original non-condensing oil boiler. The renovated dwelling with the lowest LF was characterised by optimised installations, 10 cm EPS insulation at the front facade (maximum allowed extra thickness at the street side of a dwelling), 14 cm EPS insulation at the back facade and 7.5 + 22 cm rock wool in the inclined roof.

From a financial point of view and for this specific dwelling, optimising the technical installations was preferred to insulating the inclined roof and/or the exterior wall. Furthermore, insulation of the exterior wall was, grace to its lower investment costs, preferred to insulation of the inclined roof, although the latter led to a higher reduction in lifecycle costs starting from the non-insulated variant. Moreover, external insulation of the front and back facade was preferred over a combination of internal and external insulation. Finally, complete renovation (i.e. refurbishment of all four building elements) led not to lowest life cycle financial cost.

For the non-renovated terraced dwelling with a roof with original underlay (variant on reference) similar conclusions as for the dwelling without underlay could be drawn. However, some differences were noticed. The remaining lifecycle costs for the non-renovated dwelling with underlay were lower than for the reference, due to the heat resistance of the wood-fibre board underlay (lower heating costs). Furthermore, the investment costs for insulating a roof without underlay were higher, due to the necessary additional interventions (i.e. removal and replacement of the existing ceramic roof tiles and tile laths) in order to add an underlay before being able to put the insulation.

ENVIRONMENTAL COST

In FIGURE 20, the initial (IE) and lifecycle (LE) environmental costs of all renovated dwellings are given, compared to the remaining lifecycle environmental cost of the reference non-renovated dwelling (green dot at IE = 0 €).

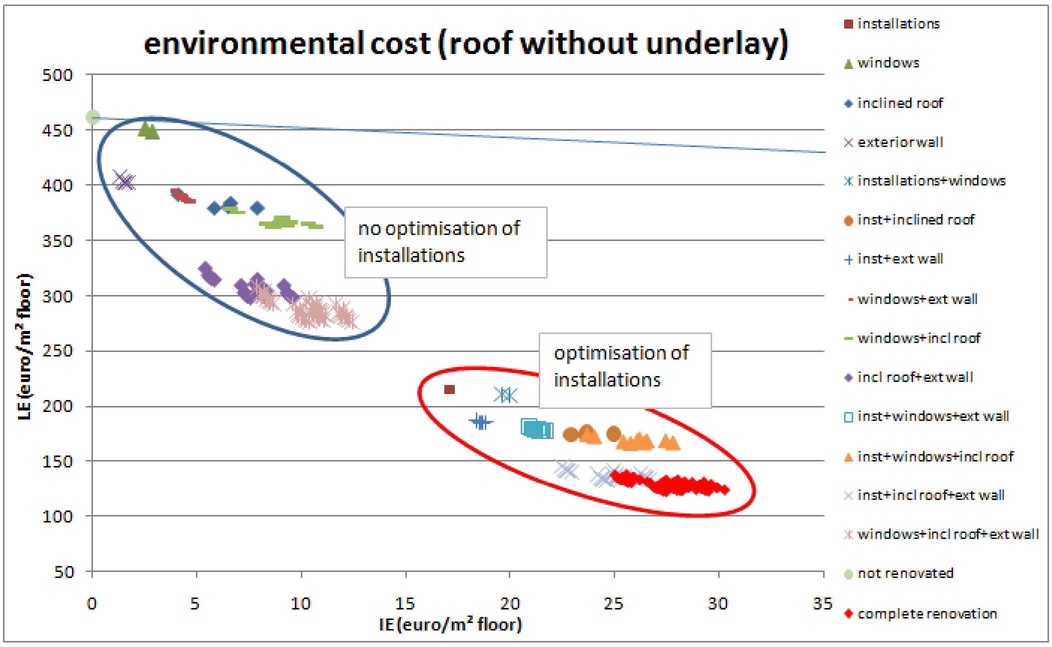


FIGURE 20 Terraced dwelling, type 1 (period before 1945): initial (IE) and lifecycle (LE) environmental costs for all renovation variants, including the non-renovated reference dwelling (roof without underlay) (service life: 60 years)

All renovation variants were characterised by a lower lifecycle environmental cost than the remaining cost of the non-refurbished variant. All considered refurbishment measures were thus interesting from an environmental point of view.

Replacing windows resulted in the lowest reduction in lifecycle costs, while, as was also the case for the financial costs, the largest reduction in lifecycle environmental costs was obtained by optimisation of the technical installations. Similar reasons as for the financial evaluation could be given here. Furthermore, in this case and in contrast to the financial costs, insulation of the exterior wall and/or the inclined roof also resulted in significant reductions in lifecycle environmental costs in comparison to the non-insulated dwelling. These actions were also characterised by lower initial environmental costs than the optimisation of the installations. Moreover, renovation of all four building elements (i.e. complete renovation) led to the lowest lifecycle environmental costs of all dwelling variants. The renovated dwelling with the lowest LE was characterised by optimised technical installations, wooden window frames with triple glazing, 18 cm EPS insulation at both the front and back facade (maximum thickness analysed) and 7.5 + 22 cm rock wool in the inclined roof.

From an environmental point of view and specifically for this dwelling, insulation was preferred to optimisation of the technical installations. Furthermore, insulation of the exterior wall was preferred to insulation of the inclined roof.

The latter was mainly due to the higher investment costs related to the installation of an underlay before putting in place the insulation, which were not compensated by the larger energy-efficiency of the insulated roof compared to the insulated exterior wall. The lowest lifecycle environmental costs could be obtained by combining all four refurbishment measures.

For the non-renovated terraced dwelling with a roof with original underlay (variant on reference) similar conclusions as for the variant without underlay could be drawn. The order of priority of actions did not change. As was also the case for the financial costs, both the initial costs for roof insulation and the remaining lifecycle environmental costs for the dwelling with original underlay were smaller than for the dwelling without underlay.

TOTAL COST

Concerning the total cost (i.e. financial + environmental cost), similar conclusions as for the financial costs could be drawn. However, the option with the lowest LT differed from the one with the lowest LF and consisted of a combi condensing gas boiler, 10 cm EPS wall insulation at the front facade and 18 cm EPS wall insulation (instead of 14 cm) at the back facade, combined with 7.5+22 cm rock wool in the roof. For the non-renovated dwelling with original underlay, similar conclusions as for the dwelling without underlay could be drawn.

K- AND E-VALUE AND OVERHEATING

Because all renovation measures focused on energy efficiency, these all resulted in an important decrease in both K- and E-values. K-values below 45 (mandatory level for new dwellings) were obtained by insulating both the inclined roof and the exterior walls. E-values below 80 (mandatory level for new dwellings) were obtained by optimising installations in combination with roof and exterior wall insulation, as well as by a combination of all renovation measures (i.e. complete renovation).

Enhancing the insulation level (and air-tightness) of a dwelling for energy-saving reasons could possibly lead to overheating problems in summer. An overheating indicator (OI) above 17.500 Kh indicates that active cooling will most probably be installed (a.a. 2005b). An OI between 8.000 and 17.500 Kh is experienced as uncomfortable and therefore the chance the inhabitants will install active cooling is real. Infrequent overheating can be solved by temporarily opening windows or providing shading devices (which is preferred to active cooling). For the renovated terraced dwelling, an OI above 8.000 Kh was obtained in case of thick insulation of both the exterior walls and the inclined roof. However, for all cases the OI remained far below 17.500 Kh.

DWELLING SERVICE LIFE OF 120 YEARS

For a prolonged service life of 120 years, similar results as for a service life of 60 years were obtained. The only difference was that replacing windows became more profitable from a financial point of view (cf. lifecycle costs for dwellings with windows with double or triple glazing were now lower than for the non-renovated dwelling consisting of windows with single glazing).

FURTHER USE, RENOVATION or NEW CONSTRUCTION?

In FIGURE 21, the initial (IF) and lifecycle (LF) financial costs for further use of the non-refurbished dwelling, renovation and new construction are shown.

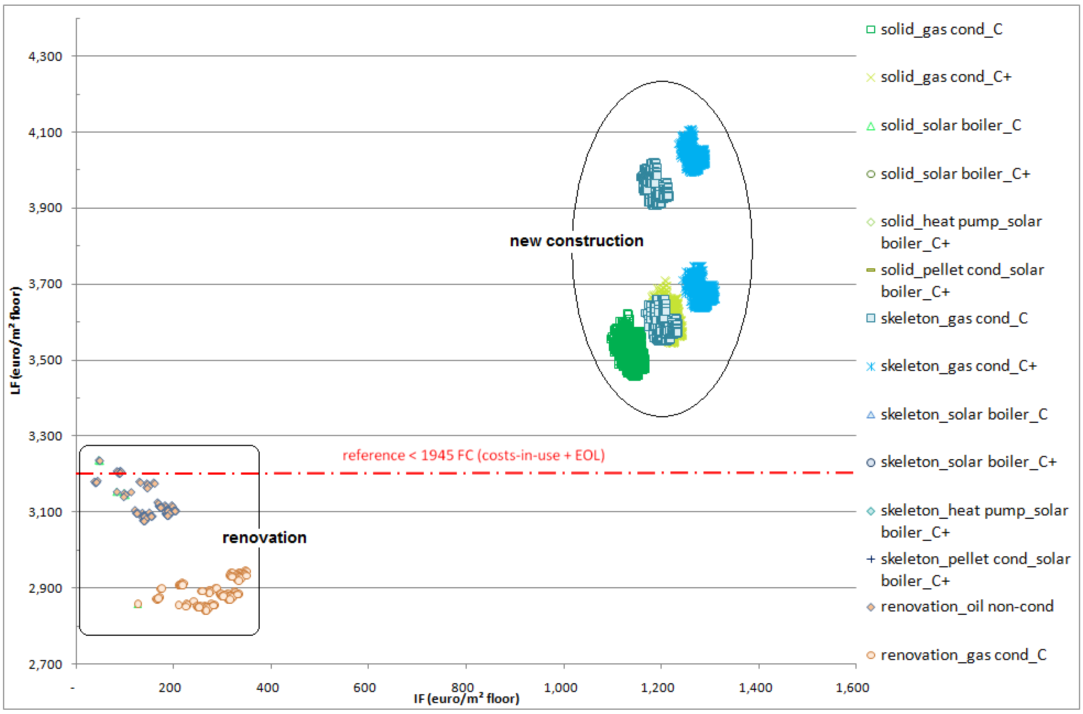


FIGURE 21 Terraced dwelling, type 1 (period before 1945): Initial (IF) and lifecycle (LF) financial costs for further use of the dwelling (reference < 1945 FC), renovation of the dwelling and new construction – dwelling service life: 60 years

The newly-built variants were characterised by both higher initial and lifecycle financial costs than further use of the existing dwelling. The lifecycle financial costs of most renovated dwelling variants were lower than the remaining financial costs for further use of the non-renovated dwelling. Energy-saving refurbishment was for this dwelling thus identified as most preferred option.

In FIGURE 22, the initial (IE) and lifecycle (LE) environmental costs for all three options for the here considered terraced dwelling are given.

From an environmental point of view, the renovated dwelling variants were characterised by lower initial and slightly lower (i.e. part of renovated dwellings with optimised installations), similar (i.e. part of renovated dwellings with optimised installations) or higher (i.e. renovated dwellings with original technical installations) lifecycle environmental costs compared to the newly-built variants. Further use of the non-renovated dwelling resulted in the highest lifecycle environmental costs.

Consequently, renovation and new construction were preferred to further use of the existing building. Only in the case of complete renovation or optimisation of technical installations, combined with roof and exterior wall insulation, renovation could be preferred to new construction of a similar building (cf. slightly lower lifecycle costs and lower initial costs).

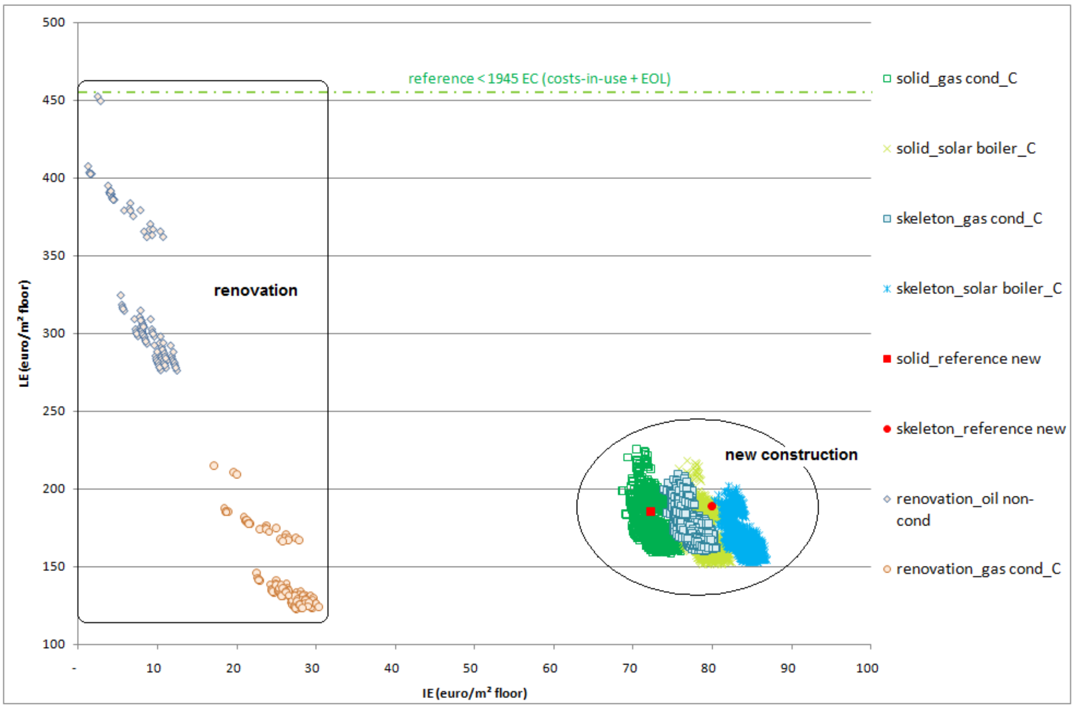


FIGURE 22 Terraced dwelling, type 1 (period before 1945): Initial (IE) and lifecycle (LE) environmental costs for further use of the dwelling (reference < 1945 EC), renovation of the dwelling and new construction (service life: 60 years)

For a prolonged service life of 120 years, most of the new dwellings had lower lifecycle financial costs than the remaining costs for further use of the non-refurbished dwelling. However, renovated dwellings, in which the original technical installations were improved, still had lower initial and lifecycle financial costs than their newly-built alternatives. Consequently, renovation still remained the preferable option from a financial point of view. From an environmental point of view, similar conclusions as for a dwelling service life of 60 years were drawn. Complete renovation was still characterised by the lowest initial and lifecycle environmental costs.

Detached dwelling, type 3 (period 1971-1990)

The dwelling is a one-floor building (i.e. bungalow), built between 1971 and 1990. An overview of the four refurbished building elements with their reference composition and the applied renovation measures is given in TABLE XIX.

TABLE XIXa Detached dwelling, type 3 (period 1971-1990): overview of the reference composition and the different renovation measures (part A)

Building element	Reference composition	Renovation measures
exterior wall *(the height of the exterior wall depends on the overall thickness of the flat roof)*	• *brick veneer 9 cm* • *air cavity 3 cm* • *cavity ties* • *rock wool cavity insulation 2 cm* • *loadbearing brick 30 cm* • *gypsum plaster* • *acrylic paint*	• ***stucco on insulation:*** o *EPS insulation: 6cm, 10cm, 14cm, 18cm* • ***internal insulation behind a new brick veneer*** o *demolition of old brick veneer and removal of old insulation* o *new brick veneer 9 cm* o *rock wool insulation (RW): 6cm, 10cm, 14cm, 18cm* o *cavity ties* • ***injection of existing air cavity*** o *PUR foam (3 cm)*
flat roof	• EPDM 1,2 mm • rock wool 6 cm • PE vapour felt – glass fibre reinforced • sloping concrete layer (average) 6cm • precast hollow slab – reinforced concrete 16,5 cm • gypsum plaster • acrylic paint • XPS edge insulation **roof edge:** • aluminium roof edge profile 6 cm overlap • EPDM 1,2 mm • PUR 3 cm • plywood water resistant board 18 mm	• **thermal insulation + external finishing:** o *EPDM 1,2 mm* o *PUR: 10cm, 17cm, 2 x 12cm* o *PE vapour felt – glass fibre reinforced* **roof edge:** • aluminium roof edge profile 6 cm overlap • EPDM 1,2 mm • PUR 3 cm • plywood water resistant board 18 mm *(width of roof edge is in function of refurbishment dimensions of exterior walls)*

TABLE XIXb Detached dwelling, type 3 (period 1971-1990): overview of the reference composition and the different renovation measures (part B)

Building element	Reference composition	Renovation measures
windows	• old wooden frame • standard double glazing 4/12/4 • aluminium or steel spacer	• **new wooden windows with thermal improved double glazing:** o removal of old frame and glass o standard wooden frame o double glazing o thermally improved spacer
technical installations	• gas burner, combi, instant • galvanised steel pipes for gas supply • gas exhaust, aluminium and steel rain cap • circulation pump and expansion vessel • PP sanitary drainage pipes • Shallow-walled steel pipes for heat distribution • standard panel radiators • thermostatic valves and room thermostat • no ventilation system	• ***improvement of heating system and installation of ventilation system:*** o condensing gas boiler, combi, instant o PE heat distribution pipes o standard panel radiators o thermostatic valves and outside temperature sensor o ventilation unit system C, including ducts and internal grids o removal of gas burner and distribution pipes

FINANCIAL COST

In FIGURE 23 the initial and lifecycle financial costs of all refurbishment cases are compared to the remaining costs of the non-refurbished dwelling (i.e. the green dot).

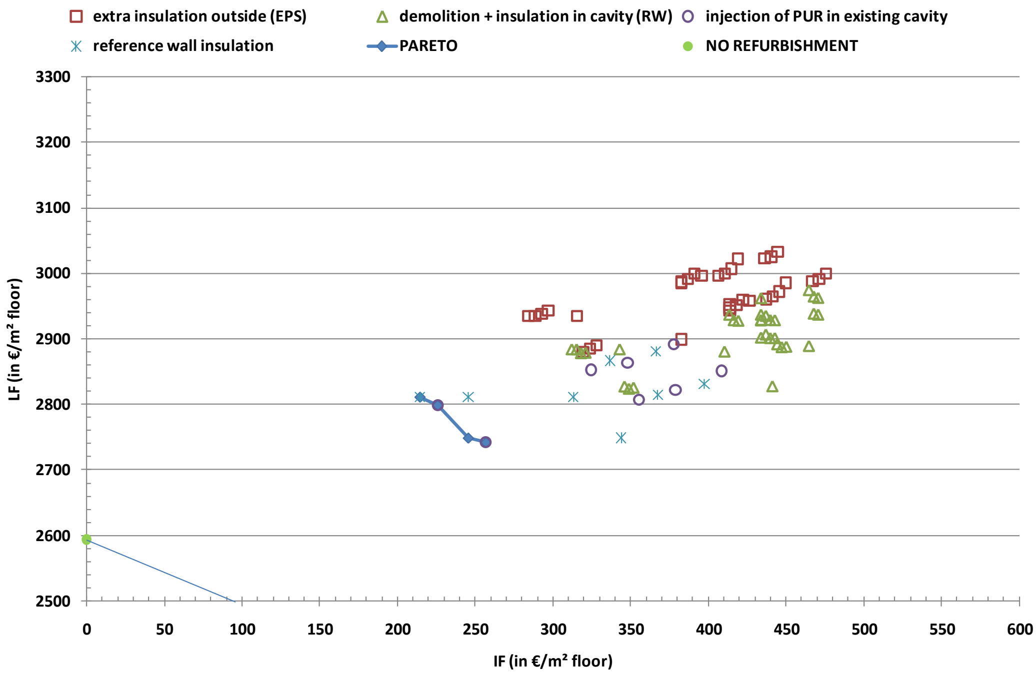


FIGURE 23 Detached dwelling, type 3 (period 1971-1990): Initial and lifecycle financial costs for all renovation variants, incl. the non-renovated dwelling (life span: 60 years)

The dwelling variants are primarily grouped according to the type of refurbishment measures for the external walls.

All dwelling variants were characterised by a lifecycle financial cost that was higher than the remaining financial cost for the non-refurbished dwelling. This means that for this relatively modern dwelling and a dwelling service life of 60 years the proposed measures were not interesting from a financial point of view. The dwelling variant with the lowest lifecycle cost is still approximately 150€/m² floor more expensive than the unaltered dwelling.

ENVIRONMENTAL COST

In FIGURE 24 the initial and lifecycle environmental costs of all refurbishment cases were compared with the remaining costs of the non-refurbished dwelling (i.e. the green dot).

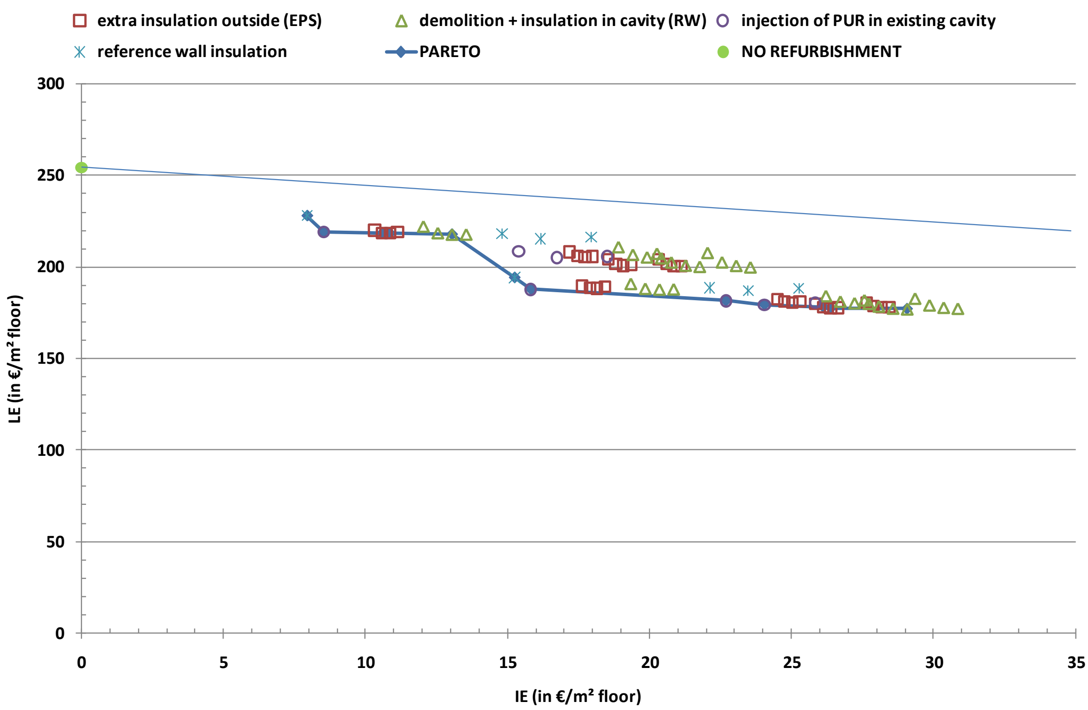


FIGURE 24 Detached dwelling, type 3 (period 1971-1990): initial and lifecycle environmental costs for all renovation variants, incl. non-refurbished dwelling (life span: 60 years)

All renovation cases resulted in a lower lifecycle environmental cost than the remaining cost of the non-renovated dwelling. Furthermore, all renovation variants were situated below the 45° line. Consequently, all measures led to a reduction in lifecycle costs that was larger than twice the required initial cost. The considered renovation measures for this dwelling were thus always a good idea from an environmental point of view. The most effective measures are shown in TABLE XX.

TABLE XX Pareto solutions for environmental costs – dwelling service life: 60 years*

windows	exterior walls	flat roof	technical services	IE (€/m² floor)	LE (€/m² floor)
thermal	-	-	-	7,95	228,04
thermal	PUR 3cm	-	-	8,52	219,24
thermal	EPS 10cm	-	-	10,59	218,60
thermal	EPS 14cm	-	-	10,86	218,38
thermal	RW 14cm	-	-	13,04	217,88
thermal	-	-	improved	15,25	194,23
thermal	**PUR 3cm**	**-**	**improved**	**15,83**	**187,74**
thermal	PUR 3cm	PUR 10cm	improved	22,69	181,53
thermal	PUR 3cm	PUR 17cm	improved	24,05	179,43
thermal	EPS 10cm	PUR 17cm	improved	26,12	178,13
thermal	EPS 14cm	PUR 17cm	improved	26,39	177,49
thermal	RW 8cm	PUR 17cm	improved	29,07	177,11

*detailed information about the composition of each element is given in TABLE XIX.

Injection of PUR foam into the existing exterior walls was preferred above external insulation and a new cavity wall with rock wool insulation. Furthermore, replacement of technical services was preferably performed after the insulation improvement of the walls. For the case presented – a relatively modern detached dwelling – further insulating the flat roof was usually the last refurbishment measure to be taken. The roof of the existing dwelling was already insulated and its surface area is relatively small compared to the external walls. From an environmental lifecycle cost perspective, a complete energy-saving refurbishment (i.e. of all named elements) was preferred to a selective one.

TOTAL COST

In FIGURE 25 the total costs (IT and LT) of all refurbishment cases are compared with the corresponding costs of the non-refurbished dwelling (i.e. the green dot). Initial and lifecycle environmental costs represented respectively 5% and 6% of the corresponding total costs. This explains why the same conclusions were drawn for the total costs as for the financial costs: for a life span of 60 years none of the proposed refurbishment measures were interesting for this relatively modern dwelling.

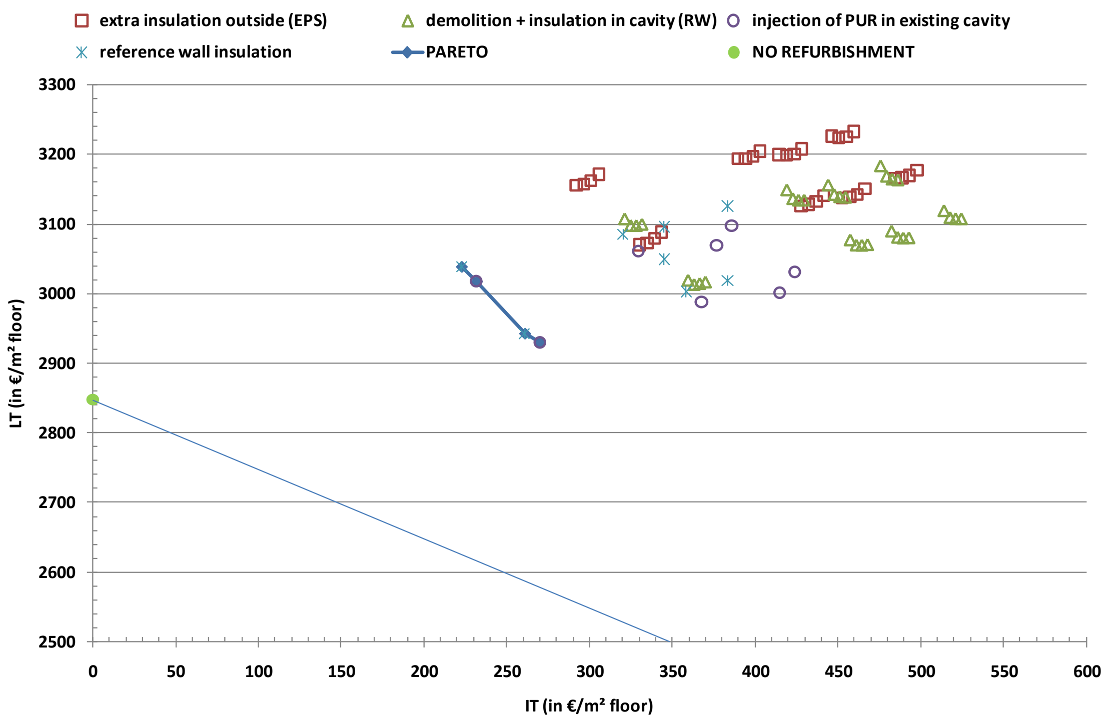


FIGURE 25 Detached dwelling, type 3 (period 1971-1990): Initial and lifecycle total costs for all renovation variants, incl. the non-refurbished dwelling (life span: 60 years)

K- AND E-VALUE AND OVERHEATING

All energy-saving measures led to lower K- and E-values compared to the non-refurbished dwelling. An insulation of K45 – which is mandatory in Belgium for new dwellings – can only be obtained when flat roof and exterior walls are maximally insulated, respectively with 24cm PUR and 18cm EPS (at the outside), windows are replaced and technical services are improved. An E-value below 80 – which is mandatory in Belgium for new dwellings – can only be obtained through a complete renovation. Because the overheating indicator of all studied cases was always below 17.500 Kh (maximum of 10.176 Kh for complete refurbished dwelling) overheating was not problematic.

DWELLING SERVICE LIFE OF 120 YEARS

From an environmental point of view, the same trends as for a life span of 60 years were visible. Because the environmental costs of all dwelling variants were situated below the 45° line, all studied energy saving measures for a life span of 120 years were characterised by a net gain in environmental cost greater than the investment cost. From a financial and total perspective important changes were identified for this prolonged life span.

Although none of the solutions were situated below the 45° line, some refurbishment measures had a lower financial and total lifecycle cost than the remaining costs of the non-refurbished dwelling. This indicates that the energy-saving measures become more interesting on the long term.

FURTHER USE, RENOVATION or NEW CONSTRUCTION?

In FIGURE 26 the initial (IF) and lifecycle (LF) financial costs for all three options (further use non-refurbished dwelling, renovation or new construction) are shown.

Although newly-built buildings have the lowest heating costs, they are characterised by higher initial and periodic financial costs compared to the studied refurbishment cases. Furthermore, the reference building without any refurbishment measures was identified as the most cost effective option, since it has the lowest lifecycle financial cost. It is in close competition with some of the studied renovation cases.

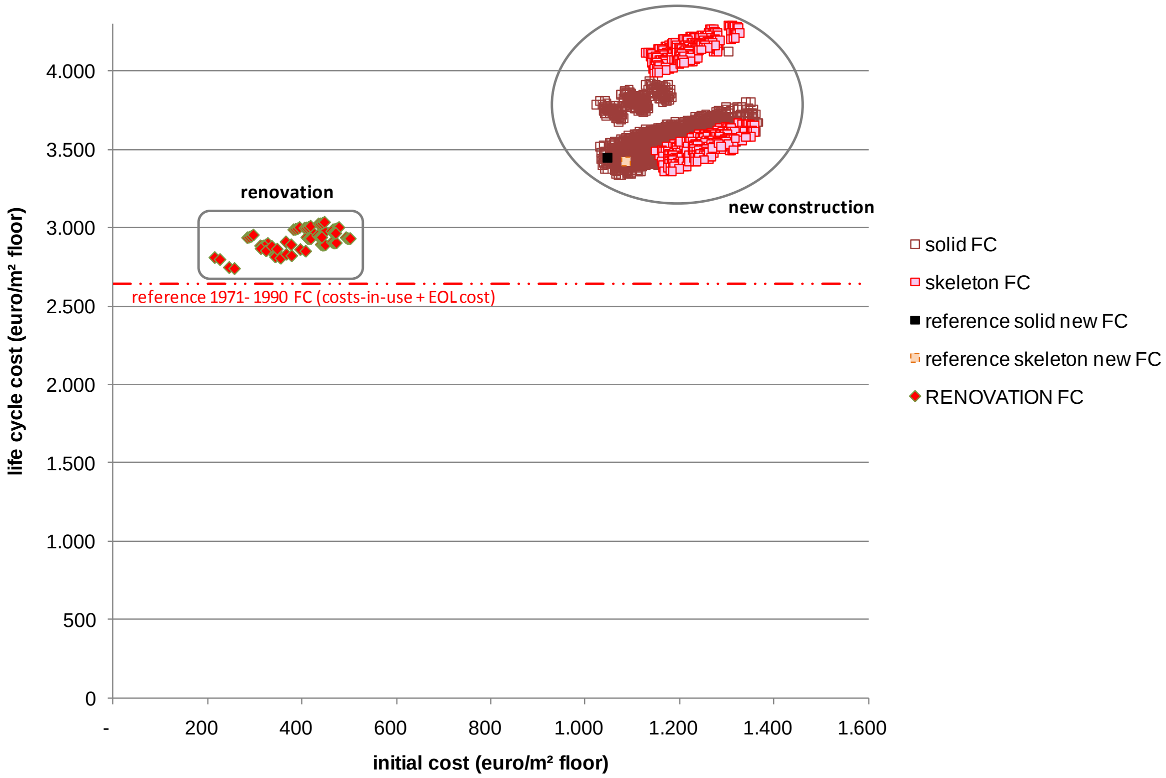


FIGURE 26 Detached dwelling, type 3 (period 1971-1990): Initial and lifecycle financial costs for further use of the dwelling, renovation of the dwelling and new construction (service life: 60 years)

From a lifecycle environmental perspective energy-saving refurbishment measures are preferred above new low energy dwellings (FIGURE 27). The low initial environmental costs of the energy-saving refurbishment measures compensate for the still high heating costs of the renovated dwellings compared to the newly built variants.

Environmental heating costs of new dwellings are lower mainly due to a higher insulation rate (e.g. ground floor).

All renovation cases and most of the newly-built variants are characterised by a lower environmental lifecycle cost compared to reference non-refurbished dwelling.

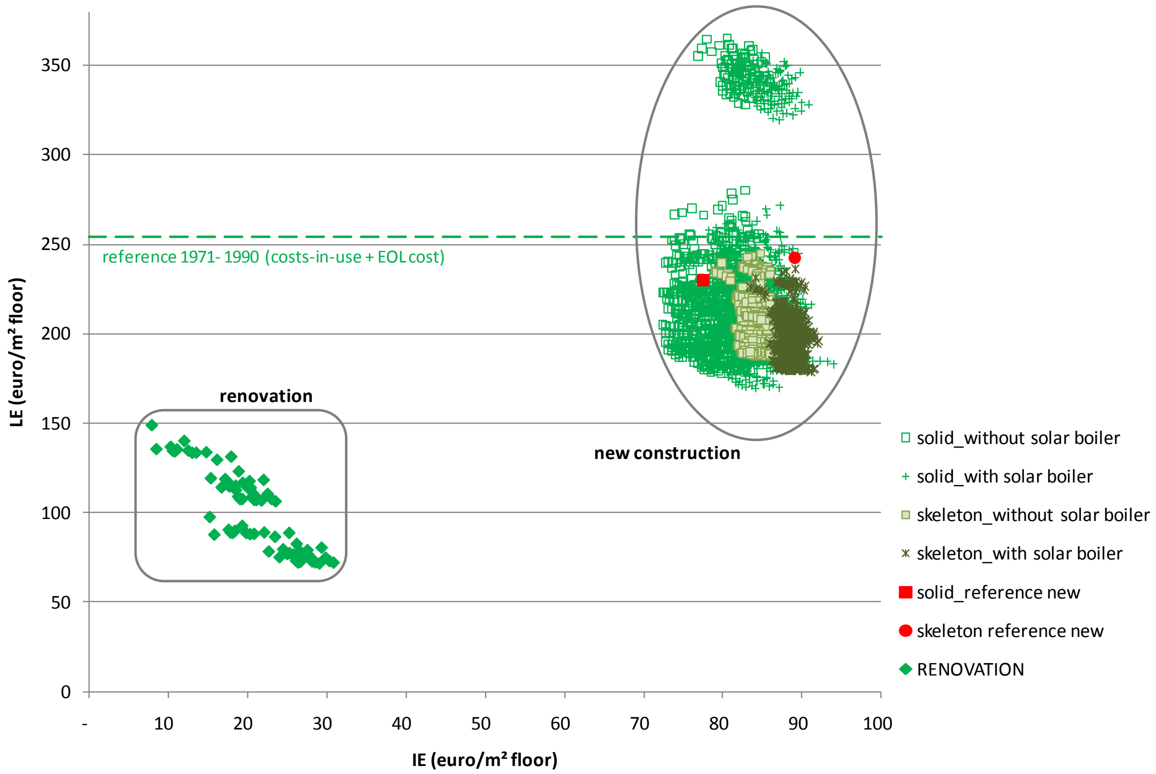


FIGURE 27 Detached dwelling, type 3 (period 1971-1990): Initial and lifecycle environmental costs for further use of the dwelling, renovation of the dwelling and new construction (service life: 60 years)

From a total cost perspective (FIGURE 28), similar conclusions can be drawn as for the financial costs. Periodic costs are the most important cost for all cases. The reference building without refurbishment actions has the biggest heating costs, while the renovation cases are characterised by the lowest initial costs compared to the new dwelling variants.

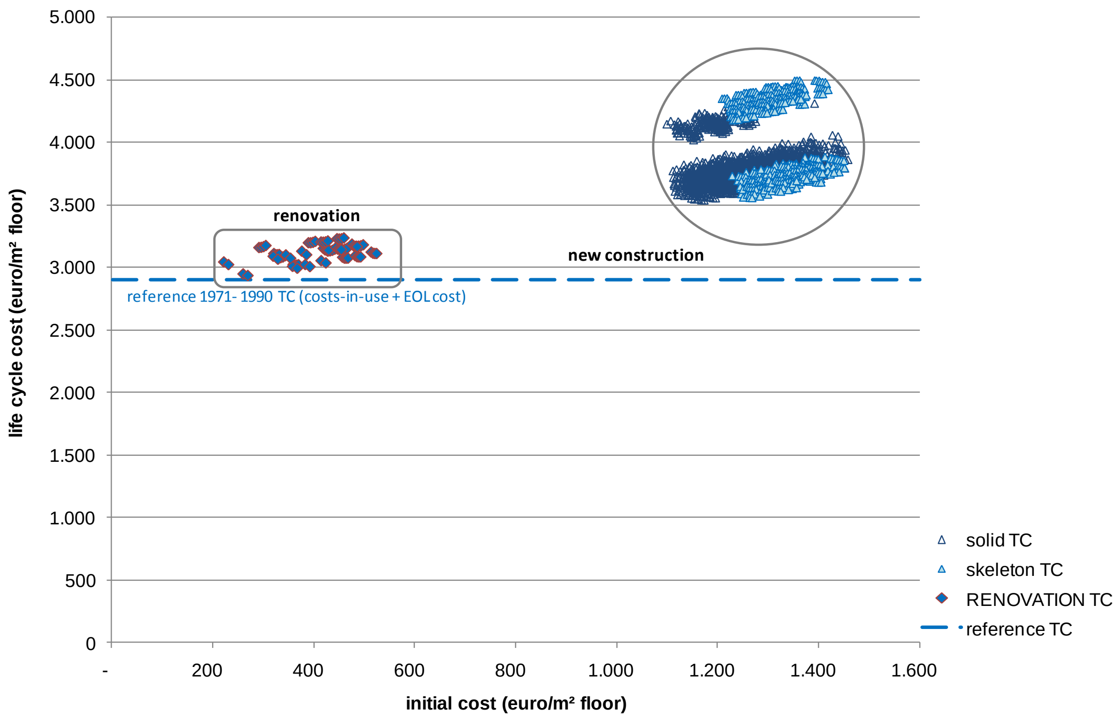


FIGURE 28 Initial and lifecycle total costs for further use of the dwelling, renovation of the dwelling and new construction variants. (service life: 60 years)

For a prolonged life span of 120 years, most renovation cases become financially more interesting than further using the non-refurbished dwelling. From a financial perspective newly-built dwellings still lead to the highest lifecycle costs, although their lifecycle costs are now closer to the remaining costs of the reference dwelling. Conclusions concerning total costs are in line with the financial costs.

Regarding lifecycle environmental costs, renovation measures cannot compete anymore with new low energy dwellings. The small initial costs of the renovation measures cannot compensate the high (environmental) heating costs over 120 years compared to the new low energy dwellings.

Conclusions on assessment of renovation measures

Considering renovation of the terraced dwelling, built before 1945, replacing the heating and hot water installations by a combi condensing gas boiler and installing a ventilation system C was preferred from a financial point of view, while from an environmental perspective, insulation of the exterior wall and the inclined roof was the best solution, followed by an optimisation of the technical installations. For this particular building, replacing windows was not interesting from a financial point of view and only of small interest from an environmental perspective.

Furthermore, all renovated dwelling variants with optimisation of initial technical installations were characterised by lower initial and lifecycle financial, environmental and total costs than newly built alternatives or further use of the non-renovated dwelling. Consequently, the here considered renovation was preferred, followed by new construction of a similar dwelling and at last further use of the non-refurbished dwelling.

As the detached dwelling, built between 1971 and 1990, was already insulated to a certain level, not renovating proved to be the most cost effective option for a service life of 60 years. However, when prolonging the service life up to 120 years, renovation competed with both further use and new construction of a low energy dwelling. Therefore, regarding decision making (further use or renovation of existing dwelling or construction of a new one), the uncertainty of the service life of dwellings is an important parameter to take into account.

Outputs:

i. Internal research reports
   - Janssen, A., Delem, L., Allacker, K., De Troyer, F. and Debacker, W. (2010). Final report on methodology – focus on renovation – plus future prospects, BELSPO, 71 pages.

e. Evaluation of current policy measures

The SuFiQuaD policy evaluation procedure elaborated in section 2-v made the assessment of some existing financial incentives for dwellings possible. Because the majority of current financial support from local, regional and federal governments aims at the enhancement of energy efficiency in dwellings, the focus in the SuFiQuaD project was put on current policy relating to this theme. In this report, the results on financial support regarding photovoltaic panels and insulation of the dwelling roof are elaborated in detail, while the results on other relevant policy measures are summarised briefly.

Photovoltaic panels

DESCRIPTION OF CURRENT POLICY MEASURES

Since prices of PV systems drastically changed over the last years, financial support measures applicable to the first quarter of 2010 and 2011 were evaluated instead of the situation of 2008. An overview of the studied incentives is shown in TABLE XXI.

TABLE XXI Overview of studied financial incentives: first quarter of 2010 and first quarter of 2011

Level	type of support	amount	Restrictions
Federal	*tax refund*	*40% on installation cost (including VAT) + 8% individual tax*	• *max. 3600€* • *if the dwelling is older than 5 years, the tax refund can be spread over 4 tax years*
Flemish region	*green energy certificates*	*350€* for each 1000kWh electricity production*	• *roof insulation is mandatory (R_{min} = 3m².K/W)* • *max. period: 20years***
	communal grant	*variable according to commune; for the town Ieper: 15% on installation cost (including VAT)*	• *max. 620€ (specific to the commune)*
Brussels Capital region	*green energy certificates*	*150€ for each 1000kWh electricity (bought by Belgium's transmission system operator)*	• *max. period: 10 years*
	regional grant	*1,00€/Wp****	• *max. 30% of installation cost* • *only for new passive dwellings (heating demand < 15 kWh/m².year) and low energy renovation (heating demand < 60kWh/m².year)*
	communal grant	*variable according to commune; for the commune of Anderlecht: 10% of investment cost (including VAT)*	• *max. 1000€ (specific to the commune)* • *only granted when the regional grant is not applicable (specific to the commune)*
Walloon region	*green energy certificates*	*150€ for each 1000kWh electricity (bought by Belgium's transmission system operator)*	• *max. period: 15 years*
	*regional grant*****	*20% of investment cost*	• *max. 3500€*
	communal grant	*variable according to commune; median: 250€*	

* In 2011 this value is reduced to 330€/1MWh electricity production during 20 years.
**From 2013 green energy certificates in Flanders are limited to 15 years.
*** For 2011 the regional grant in the Brussels Capital region is dependent of the taxable income. For a yearly individual income between 30.000 and 60.000€, a regional grant of 0,50€/Wp is given (same restrictions as for 2010).
**** For PV installations younger than March 2010, this regional grant is abolished.

Financial support regarding photovoltaic panels strongly differs from region to region. In case structural changes are made to support mechanisms between 2010 and 2011, these are mentioned.

ANALYSIS OF CURRENT POLICY MEASURES ON PV PANELS

The analysis focuses on the assessment of the financial support system in 2010 for each region. A sensitivity analysis was performed for the current situation, i.e. first quarter of 2011.

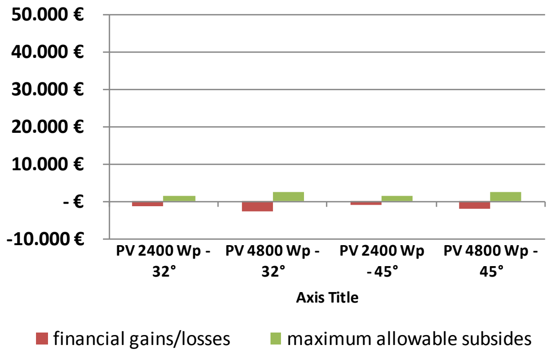


FIGURE 29: financial gains/losses vs. maximum allowable financial support in the **Flemish region** for installation of PV in 2010

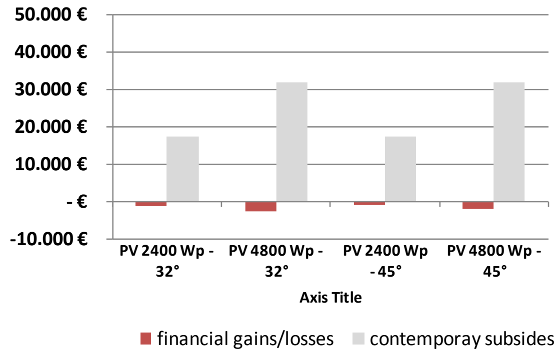


FIGURE 30: financial gains/losses vs. financial support in the **Flemish region** for installation of PV in 2010

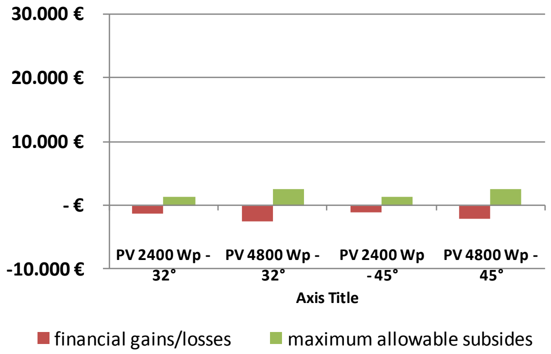


FIGURE 31: financial gains/losses vs. maximum allowable financial support in the **Brussels Capital region** for installation of PV in

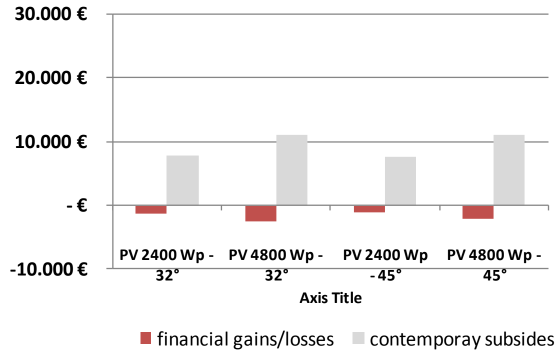


FIGURE 32: financial gains/losses vs. financial support in the **Brussels Capital region** for installation of PV in 2010

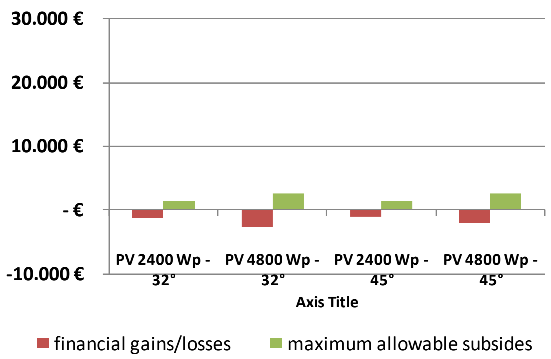


FIGURE 33: financial gains/losses vs. maximum allowable financial support in the **Walloon region** for installation of PV in 2010

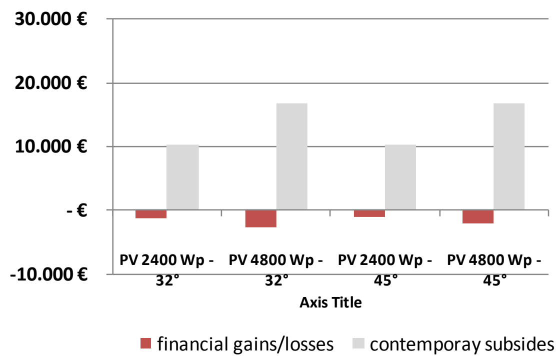


FIGURE 34: financial gains/losses vs. financial support in the **Walloon region** for installation of PV in 2010

Although the investment costs of PV systems dropped drastically over the last years– from 5,97€/Wp in June 2008 (Aspen 2008a) to 3,55 in February 2010 (Solart Systems 2010) – the installation of a typical PV system with a life span of 20 years in 2010 still generated financial losses – i.e. without financial support from the government and compared to central electricity production in Belgium. FIGURE 29, FIGURE 31 and FIGURE 33 show that financial support measures from the government in the first quarter of 2010 over-compensate these losses.

Already after the first year the relative lifecycle losses are gained back, from 1 to 5 times for the studied capacities, mainly through federal tax reduction and in Wallonia additionally thanks to regional grants. From March 2010 this Walloon grant was abolished. For all regions green energy certificates help to accumulate annually profits for a period of 10 years for the capital region, 15 years for the Walloon region and 20 years for the Flemish region. In Flanders this leads to a complete payback of the initial investment after 8 to 10 years for respectively the 2400Wp and 4800Wp PV system.

Since the installation of all studied PV systems lead to lifecycle environmental gains – compared to the central production of electricity – that are bigger than the corresponding lifecycle financial losses, it is justified that society financially support these energy measures (cf. FIGURE 30, FIGURE 32, FIGURE 34). Nevertheless, the cumulated value of existing financial support measures in 2010 is for the Flemish region 12 to 13 times bigger, for the capital region 4 to 6 times bigger and for the Walloon region 6 to 8 times bigger than the lifecycle environmental gains. This very high level of support can thus not be justified based on this integrated evaluation of financial and environmental external costs. However, as mentioned before (section 2.g-v), there might be other reasons to justify the incentives.

DISCUSSION

Since all calculations for 2010 point out that PV systems lead to financial lifecycle losses – that are (slightly) smaller than the corresponding lifecycle environmental gains – the cumulated value of financial support measures should be restricted to the lifecycle environmental gains (cf. evaluation procedure). This comes along with a support limit of **0,64€/MWh electricity generated** through the PV systems.

Due to the rapid changes on the financial market and the abolishment of some support measures, the presented analyses above were repeated using indicative prices for the first quarter of 2011 and the adapted financial support systems. The analysis revealed that contrary to 2008 and 2010 (first quarter), the installation of PV systems results in small lifecycle financial gains – compared to central electricity production in Belgium – that are smaller than the lifecycle environmental gains.

According to the evaluation procedure, the cumulated value of financial support measures should be limited to the difference of the environmental and financial lifecycle gains. This results in a support limit of **0,51€/MWh and 0,39€/MWh electricity generated** through PV systems respectively for flat and pitched roofs.

The rapidly changing prices for PV systems in combination with the reduced incentives clearly show that market prices and financial incentives influence each other. The proposed approach of balance between private financial costs and societal environmental external costs therefore seems highly recommended.

Roof insulation

DESCRIPTION OF CURRENT POLICY MEASURES

In Table XXII, an overview of the relevant financial incentives for roof insulation in Belgium anno 2011 is given. Here, only incentives at the federal and the regional level, accessible to all building owners and tenants, are considered (for example, no provincial or local incentives or incentives for low income owners).

Table XXII Overview of financial incentives for roof insulation in existing dwellings in Belgium anno 2011

ROOF INSULATION			
Federal level	***Flanders***	***Walloon Region***	***Brussels Capital Region***
tax reduction: 40% of total cost max. 2770 euro/y transferable to next 3 years Rd > 2.5 m²K/W	**subsidy**: maximum 500 euro/dwelling + 2-4 euro/m² Rd > 3 m²K/W minimum 40 m²	**subsidy**: 10 euro/m² maximum 100 m² Rd > 3.5 m²K/W	**subsidy**: 20 euro/m² maximum 50% of total cost Rd > 4 m²K/W dwelling > 10 years

ANALYSIS OF CURRENT POLICY MEASURES

An analysis at both the dwelling level (specific for the terraced dwelling, built before 1945) and the element level (dwelling-independent) was performed. At the dwelling level, the assessment focused on two non-insulated inclined roofs, one without underlay (case A) and one with underlay (case B). These were insulated with either 7.5 + 10 cm or 7.5 + 22 cm rock wool between the existing wooden arrises and purlins.

The analysis at the element level focused on two inclined roofs with underlay, one initially non-insulated (case B) and one already partially insulated (7.5 cm rock wool) (case C). These were (further) insulated with either 7.5 + 10 cm or 7.5 + 22 cm rock wool (case B) or an additional 18 cm or 22 cm rock wool between the existing wooden arrises and purlins (case C). A reference service life of 60 years was taken into account.

Due to the fact that for the analyses at element and at building level slightly different hypotheses and calculation methods (e.g. EPB at dwelling level and equivalent degree days at element level) were applied, the results differ slightly. FIGURE 35 and FIGURE 36 indicate the investment costs, the financial and environmental benefits/costs, the maximum allowable subsidies and the current financial incentives for both analyses.

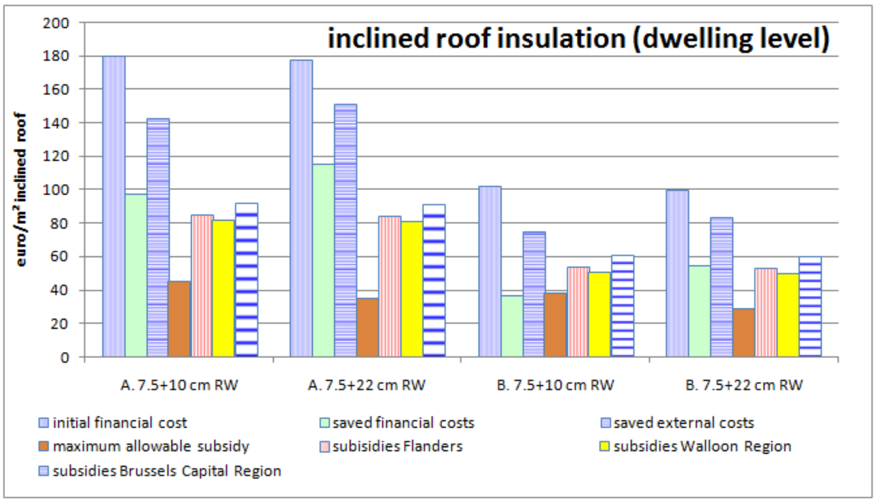


FIGURE 35 Roof insulation, analysis at dwelling level (terraced dwelling, built before 1945) (A: roof without underlay, B: roof with underlay)

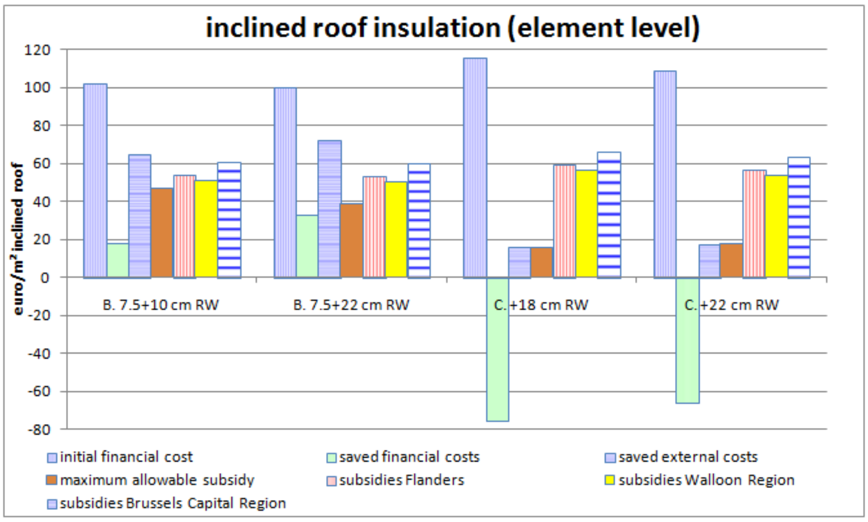


FIGURE 36 Roof insulation, analysis at element level (B: non-insulated roof with underlay, C: partially insulated roof with underlay)

DISCUSSION

The analysis at the dwelling level (FIGURE 35) indicates that insulating the existing roof leads to savings in lifecycle environmental and financial costs.

Consequently, it is justified to stimulate this measure, but it is not absolutely necessary to give financial incentives. However, as the benefit for society is larger than the financial benefit for the owner, a certain subsidy, defined by the difference between savings in lifecycle environmental and financial costs, could be justified. The current subsidies appear to be too high, since they exceed the maximum allowable subsidy. However, they remain below the value for the environmental benefit.

The analysis at the element level (FIGURE 36) leads to lower financial and environmental savings for case B, which is due to the differing energy calculation method. Here, the magnitude of current subsidies is certainly adequate because they are approximately equal to the difference between lifecycle environmental and financial benefits. However, increasing the insulation thickness of a partially insulated inclined roof (case C) resulted in negative financial savings, but positive savings in lifecycle environmental costs. The latter furthermore did not counterbalance the financial deficit, so that in this case financial incentives are not useful.

Other insulation measures and replacement of windows

Similar analyses for other insulation measures and for the replacement of windows were performed. It could be concluded that an increase in current subsidies for exterior wall insulation can be justified, while current subsidies for other measures are either too high (e.g. wooden window frames with double glazing), not necessary (e.g. replacement of glazing and cellar ceiling insulation) or not justified (e.g. extra insulation of exterior wall, insulation of floor on grade and highly insulating wooden window frames with triple glazing).

Replacement of non-condensing heating furnaces

Financial support measures related to the replacement of an old non-condensing oil or gas furnace by a condensing oil or gas furnace, an air/water or ground/water (horizontal exchange) heat pump or a condensing pellet furnace were evaluated for the three regions, for a detached dwelling built between 1971 and 1990 (K75). Although replacement resulted in net environmental gains, ranging from 40€ to 6800€, over an estimated life span of 20 years of the heat production system, only substitution by a condensing gas furnace provided life cycle financial gains as well. These environmental and financial gains are more or less equal. Furthermore, the life cycle financial losses related to the replacement by the other heat production systems were higher than the related estimated environmental gains. This means that, according to the evaluation procedure described in section 2-v, financial support for all studied replacement measures makes no sense.

Conclusions

To date, the government invests greatly in energy efficiency measures through tax reduction, green energy certificates and regional and local grants. The investigation of a number of incentives proved that the cumulative effect of some financial incentives is unjustified. Furthermore, some existing incentives could be increased, lowered or even abolished. It can therefore be concluded that each policy incentive should be carefully considered and be based on the analysis of both financial and environmental external lifecycle costs.

4. POLICY SUPPORT

a. Introduction

The SuFiQuaD project developed a powerful and extendable model to assess simultaneously a large number of building solutions for dwellings on their environmental, financial and quality performance. Several representative Belgian apartments, terraced houses, semi-detached houses and detached houses were analysed with the developed model.

By expressing the environmental performance in an external cost and by splitting up both initial and lifecycle cost, the best choices for building solutions could be derived. This was done based on several perspectives: strictly initial financial cost, lifecycle financial cost, strictly initial environmental cost, lifecycle environmental cost and total cost (financial + environmental, both initial and lifecycle). The first two are relevant for the economic self interest for the end-user, which is not per se identical to actual behaviour. The environmental costs are representing the data for the societal interest which evidently is important from the environmental policy perspective. The total cost, obtained by internalisation of the external environmental costs, is an important argument for justifying governmental action in environmental policy.

Beside the analyses reported, it is clear that many more scenarios can be simulated (e.g. cleaning, maintenance and replacement frequencies, efficiency of installations, user behaviour and innovative materials) in accordance to the subject of interest.

b. Conclusions with policy relevance

Conclusions with policy relevance are described in the subsequent paragraphs based on several analyses with the SuFiQuaD model. Rather than a comprehensive analysis/assessment/overview, it is an illustration of the strength of the developed methodology and assessment model to evaluate current policy measures and proposals for future measures.

i. **Scope** of the SuFiQuaD model

Key messages:

- SuFiQuaD is focusing on dwellings (incl. orientation) and building elements. The important estimated dwelling life span is varied between 30, 60 and 120 years to reach robust conclusions. Building elements are replaced once they reach the end of their service life.
- SuFiQuaD uses the latest available environmental and cost data for currently available technical building solutions.

The solutions are, however, limited to those, whereof all necessary environmental and cost data were available. No estimates for uncertain future developments were made. A discount rate and growth rates (materials, labour and energy) are included for lifecycle calculations. Different scenarios are considered for these rather uncertain important economic parameters.

- Although the study does not focus on spatial planning, a rough estimation of transport of the inhabitants showed on average roughly the same amount of costs (both environmental and financial) as for using their dwelling. This shows the importance of dwelling location.

ii. Conclusions on financial and external costs at **element level**

Key messages:

- Environmental external costs of building elements represent on average only 6% of the total costs, whereas for heating, these external costs are much higher (on average 30%). This difference can be explained by a much higher share of man-hours for construction, cleaning and maintenance activities compared to heating. These man-hours of course do not cause any environmental impact.
- For existing and newly built dwellings according to common practice to date, heating (use phase) represents the most important part of the lifecycle environmental cost. For low energy or passive dwellings, the production phase can, however, get more important than the use phase.
- Some building materials show a high level of lifecycle environmental costs. For metal finishing materials, ceramic tiles and hemp-cotton insulation, this was due to a high initial impact for the production/cultivation of these materials. For other materials, this was due to a lower service life and therefore higher replacement rates (e.g. bitumen shingles). Wood and wood-based products often led to an unexpected high external cost due to the necessary land use. Because the uncertainty of the impact of land use is quite high, further research seems required.

iii. Examples of changes **in order of preference for building solutions**:

Starting from an existing construction or from a first design proposal, one can analyse the order of preference for improving building solutions. This analysis can be done moving from initial cost focus to lifecycle financial cost, respectively to total costs focus, including external environmental costs.

Key message:

- Respecting all measures that relate to energy consumption in the use phase and that are financially sound on a lifecycle basis only, would already be very positive for reducing the environmental costs as well.
- Current building requirements based on the Energy Performance of Buildings Directive (EPBD) are for most building elements below the economic optimum (except for roofs). Despite the above consideration that this economic optimum would already result in an important reduction in lifecycle environmental costs, it was also proven that from an environmental perspective even higher insulation thicknesses are required.

iv. Conclusions on financial and external costs at **dwelling level**

Key messages:

- The majority of the external costs occur in the use phase due to the necessary heating of a dwelling, whereas the majority of the financial costs occur in the construction and maintenance (including cleaning) phase. With budget constraints on the initial investment and a traditional initial cost focus, short term private decisions are taken with long term negative consequences. Policies should promote private decisions based on a full lifecycle perspective including external costs benefits (information campaigns, tax discounts, green loans, etc.)
- The main conclusions of the analysis at the dwelling level are summarised in section 3.c. Based on these conclusions following policy recommendations can be formulated:
    - Building prescriptions should also include efficiency constraints based on environmental life cycle costs. For example, a passive house was proved not to be always the best solution: compactness, size, building layout and window area influence strongly its efficiency.
    - For low-energy buildings, the focus of policy measures should shift to material choice which should be evaluated at the building level considering the whole life cycle.
    - Spatial planning and orientation of buildings should be addressed in the policy measures too.
    - Industrial innovation should be stimulated in order to come up to the expected building needs, for example, larger insulation thickness and heating devices with smaller capacity.

v. **Comparison** of level of external costs **with other activities**

The level of environmental external costs is a kind of indicator for policy relevance. SuFiQuaD uses a so-called hybrid approach for the calculation of environmental external costs. The backbone (approx. two/third) is formed by external costs related to specific emissions (NO_x, CO_2-equivalents, SO_2 , $PM_{2.5}$, VOC and NH_3) as developed by the leading ExternE research efforts on typically energy and transport related activities. The impacts excluded in the ExternE method are addressed using the Eco-indicator 99 approach combined with other literature sources for the monetary valuation of the impacts.

The construction of dwellings causes approx. 6-10 % external costs whereas the heating of a dwelling causes approx. 30 % of external costs. Private car transport using the same hybrid approach causes approx. 11 % of external costs.

vi. Conclusions on **renovation cases**

Key messages:

- The energy renovation package for the considered terraced dwelling, built before 1945, which evidently was not insulated at its construction, with a further life expectancy of an additional 60 years, is financially more attractive than building a similar new dwelling. The higher initial environmental costs for new construction are more or less, but not always completely, compensated through lower environmental costs during the use phase. Consequently, in some cases, renovation of the existing dwelling is preferred to new construction, due to its lower investment and lifecycle costs.
- The energy renovation package for the considered detached dwelling 1971-1990, with a further life expectancy of an additional 60 years, is financially not attractive.
- From a total lifecycle costs perspective (financial + environmental), the energy renovation package for the detached dwelling for a prolonged service span was about break even.
- In general, regarding decision making (further use, renovation of existing dwelling or construction of a new one), the specific situation regarding the service life of dwellings is a significant parameter to take into account. Important elements for the decision to construct a new one are of contextual nature: bad location, basic problems (stability, humidity, noise) that are hard to solve or undesirable functional organization of dwelling, hard to improve.

vii. Conclusions on **coverage of current environmental policy** related to external costs from dwellings

Key message:

- Current policies related to the construction or use of dwellings are aimed at energy performance of buildings (envelop and technical services), limits for production emissions for main building materials, like cement, steel, ceramics, bricks, glass and electricity production (except nuclear) through the Emission Trading System and limits to transport emissions through European standards. As most of the environmental costs of dwellings are related to these products and processes, the conclusion is that policies and policy instruments (e.g. building prescriptions, subsidies) are in place and touch the most contributing factors, the only question is whether they are tight enough to reach sustainability.

viii. Conclusions on existing **subsidies and tax discounts for energy saving measures** compared to estimated environmental cost savings.

Key message:

- The building prescriptions for newly built dwellings should become more severe on the element level, since it was proved that current prescriptions are for all building envelope elements, except for roofs, above the economic optimum.
- The existing financial incentives to make insulation and replacement of windows more attractive for consumers could in some cases be decreased or increased or even abolished, but do never exceed the environmental benefits for society.
- The financial incentives for PV panels in all Belgian regions make them very attractive for consumers and the level of incentives exceeds very significantly the estimated environmental benefits for society. From environmental perspective, this level cannot be justified.
- Existing financial support for replacement of an old non-condensing furnace makes no sense from an environmental perspective. The lifecycle financial costs of most improved heat production systems are still higher than the corresponding lifecycle environmental gains. On the other hand, replacement by a condensing gas furnace results in equal lifecycle environmental and financial gains.

- Based on the analysis of a number of policy measures, the proposed approach to evaluate financial incentives based on private financial costs and societal environmental external costs seems highly recommended.

ix. Recommended further use and development of the **SuFiQuaD model and tool**

Key messages:

- The SuFiQuaD model can serve as a good basis for evaluation of new dwellings in Belgium. The basic environmental data has been adapted to the Belgian situation regarding energy mix and typical transport processes and production data are adapted as far as possible to Belgian/European present day practice. The database should be kept up to date. The Environmental Product Declaration (EPD) program with review procedure should be used to include the environmental improvements realised for specific products.
- For renovation, only two cases were analysed. In order to draw more general conclusions, more cases should be considered due to the variety of the building stock.
- A preliminary study on low-energy and passive houses within SuFiQuaD revealed that for current applied dwelling types/geometries, these are not always the optimum from a total lifecycle perspective, including environmental costs. A thorough study on building type and characteristics in order to build these low-energy and passive houses in an efficient way therefore seems necessary.
- Extension and application of the tool to other building types (e.g. offices, schools, commercial and recreational facilities) is needed to evaluate the whole building stock.
- Adaptation and implementation of the model for analyzing expected new technologies in the future seems a further track to be elaborated.

Outputs:

i. Internal research reports

- De Troyer F., Allacker, K., Putzeys, K., Van Dessel, J., Spirinckx, C., Geerken, T. and De Nocker, L. (2008). Interim note for policy preparation, BELSPO, 14 pages.
- Putzeys, K., Allacker, K and De Troyer, F. (2008). Note on Belgian policy, BELSPO, 40 pages.
- note on policy implementation: to be finished by end of project

5. DISSEMINATION AND VALORISATION

a. Valorisation

The SuFiQuaD results were valorised in several ways. An important valorisation was achieved by translating the SuFiQuaD methodology and tool to respond to related research questions in other research projects.

- Valorisation through OVAM MMG project

  The SuFiQuaD model and database will serve as a fundament for the development of an expert evaluation tool. On demand of OVAM, The Public Flemish Waste Agency, the SuFiQuaD model will be extended regarding environmental impacts as a minimum to the ones determined by the new CEN TC 350 Standard, allowing good compatibility with a future Belgian EPD program for building products. The weighted score in terms of external costs as developed by SuFiQuaD will be maintained for decision support. The OVAM project will be focused on materials first, but the tool should allow for future extension towards other sustainability aspects like energy and water in the use phase. The experience of all SuFiQuaD partners and large part of the developed tools will be valorised in this policy relevant project for OVAM.

- Valorisation through ALBON project

  The SuFiQuaD model and database were used within the ALBON project (Janssen et al. 2010) to evaluate and provide policy advice regarding the environmental impact and resource use of a number of new construction concepts for individual dwellings and apartments in comparison to traditional construction. The model was adapted in order to obtain environmental impact results, expressed as Eco-Indicator 99 environmental impact indicators instead of costs, and to enable to calculate the use of primary resources for each of the considered construction concepts in comparison to traditional construction.

The SuFiQuaD results were furthermore valorised by using it as input for quantitative support of the Belgian Green Building Council. This was achieved through the active participation of several members of the SuFiQuaD team in the council and via written documents (e.g. Sneuvelnota: duurzaamheid meten voor "Belgian Green Building Council", Frank De Troyer, 16/04/2009).

b. Dissemination

The SuFiQuaD results have been disseminated through presentations on public events such as conferences, workshops, platforms and study days, and through presentations to specific interested stakeholders such as architectural offices, construction related federations, federal and regional authorities (e.g. OVAM, BIM, FOD Leefmilieu).

Moreover on the PhD defence of Karen Allacker many stakeholders were invited and present. An overview of these presentations is given below. The papers in conference proceeding, as listed in section 6, were also presented but are not repeated in the overview in this section.

i. Presentations K.U.Leuven:

- **Perspective EEIG, Antwerp** – 9 February 2007:
  K. Allacker, *SuFiQuaD – Sustainability, Financial Cost and Qualities of Dwelling types*.
- **PMC-BMP, Brussels** - 17 December 2007
  F. De Troyer, *Duurzaam materiaalgebruik en SuFiQuaD*.
- **Studiedag Onderzoekscentrum Space and Society, Leuven** – 21 March 2008
  K. Allacker, *Optimising the Belgian dwelling stock by integrating environmental and financial constraints*.
- **Transitie arena Duurzaam Wonen en bouwen, Brussels** - 23 April 2008
  K. Allacker, *SuFiQuaD – Sustainability, Financial Cost and Qualities of Dwelling types*.
- **BELSPO – SSD, Brussels, workshop** - 6 November 2008
  F. De Troyer, *SuFiQuaD – Sustainability, Financial Cost and Qualities of Dwelling types*.
- Onderzoeksseminarie **Bouwfysica, K.U.Leuven, Leuven** – 17 April 2009
  F. De Troyer, *SuFiQuaD – Sustainability, Financial Cost and Qualities of Dwelling types*.
- **BIM/IBGE** (and FOD Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu), **Brussels** – 25 August 2009
  F. De Troyer and K. Allacker, *SuFiQuaD – Sustainability, Financial Cost and Qualities of Dwelling types*.
- **OVAM, Mechelen** – 1 October 2009
  F. De Troyer, *SuFiQuaD – Sustainability, Financial Cost and Qualities of Dwelling types*.
- **PhD defence Karen Allacker, K.U.Leuven, dept. ASRO, Leuven** – 1 September 2010
  K. Allacker, *Sustainable building – The development of an evaluation method.*
- Forum 'Sustainable Development in the 21st century' **Tractebel/ORI** – 15 December 2010
  F. De Troyer, *SuFiQuaD – Sustainability, Financial Cost and Qualities of Dwelling types*.

ii. Presentations VITO:

- Cursus duurzaamheid en hogere milieukwaliteit voor federale ambtenaren: Levenscyclusanalyse in de bouwwereld, organised by **OVI (Federale Overheid), Brussels** - 11 October 2007
  C. Spirinckx, *Levenscyclusanalyse in de bouwwereld*
- **European Roundtable on Sustainable Consumption and Production ERSCP 2007, Basel, Switzerland** - June 2007
  C. Spirinckx, *Sustainable building: a search for an integrated method to evaluate the sustainability of dwelling types*
- **European Roundtable on Sustainable Consumption and Production, ERSCP2008, Berlin, Germany** - September 2008
  C. Spirinckx, *Sustainable Building - Search for an Integrated Method to Evaluate the Sustainability of Dwelling Types in Belgium*

- **VIBE, Ecohuis, Antwerpen** – 14 October 2009
  W. Debacker, *Evaluation of databases in the framework of the SuFiQuaD research project*

iii. Presentations CSTC:

- **BIS beurs, Gent** - 12 October 2007
  K. Putzeys, *Duurzaam bouwen – een geïntegreerde benadering*
- **Batibouw Conferentiecyclus 'Recente technieken in het duurzaam bouwen en verbouwen', Brussels** - February 2010
  K. Putzeys, *Vergelijking van de milieu-impact van verschillende constructieve oplossingen voor lage-energiegebouwen*
- **Journée thématique : Impact des constructions basse énergie sur le gros œuvre, 2ième édition, Namur** - June 2010
  L. Delem, *Comparaison de l'impact sur l'environnement de diverses solutions de construction pour les bâtiments "basse énergie"*

iv. Co-presentations : VITO / CSTC :

- **Energy - Forum, Brussels** - November 2009
  Debacker W., Putzeys K., *SuFiQuaD research project*

c. Future valorisation and dissemination

Based on IPR agreements between the SuFiQuaD partners all future publications and commercial research initiatives based on the SuFiQuaD project will be listed. An overview of future valorisation and dissemination of research results built upon the SuFiQuaD outcome will therefore be available.

6. PUBLICATIONS

a. Publications of the teams

Peer-review

i. K.U.Leuven:

International conference proceedings:

- Allacker, K. and De Troyer F. (2007). Combining environmental impact and financial cost calculations with quality assessment at the building level, Proceedings of International Conference on Whole Life Urban Sustainability and its Assessment, Glasgow, 16 pages.
- Allacker, K. and De Troyer, F. (2009). Integrated sustainability assessment of dwellings in the Belgian context, SASBE09 (3rd CIB International Conference on Smart and Sustainable Built environments), June 15-19 2009, Delft, The Netherlands, ISBN 978 90 5269373.

Doctoral dissertation:

- Allacker, K. (2010). Sustainable building: The development of an evaluation method. Doctoral dissertation, Katholieke Universiteit Leuven, Leuven, Belgium.

International journals:

- Allacker K. and De Troyer F. (2009). Optimisation of the environmental and financial cost of two dwellings in Belgium. In: International Journal of Sustainable Development and Planning (submitted, in reviewing process)
- Allacker, K. (2010). Environmental and Economic Optimisation of the Floor on Grade in Residential Buildings. In: The International Journal of Lifecycle Assessment. (submitted, in reviewing process)
- Allacker, K. and De Troyer F. (2011). Moving towards a more sustainable Belgian dwelling stock: the passive standard as the next step? In: Journal of Green Building (submitted, in reviewing process)

Others

i. K.U.Leuven:

- On the website of LIVIOS a series of (12) articles is being published focussing on parts of the PhD research of K. Allacker executed within the SuFiQuaD project and written for architects and property owners.

  www.livios.be/nl/_build/_newz/_hot/11003.asp?content=Dossier duurzame woningbouw: de aftrap!, 31/01/2011

  www.livios.be/nl/_build/_newz/_hot/11024.asp?content=Dossier duurzaam bouwen: zoektocht naar de ideale vloer, 07/02/2011

  www.livios.be/nl/_build/_newz/_hot/11057.asp?content=Duurzame woningbouw: kies de geschikte binnenwand, 14/02/2011

  www.livios.be/nl/_build/_dozz/_build/11069.asp?content=Dossier duurzaam bouwen: buitenwand kiezen, 21/02/2011

  www.livios.be/nl/_build/_dozz/_build/11091.asp?content=Duurzame woningbouw: hellend dak kiezen, 28/02/2011

www.livios.be/nl/_build/_dozz/_build/11117.asp?content=Duurzame woningbouw: plat dak kiezen, 7/03/2011

www.livios.be/nl/_build/_dozz/_build/11180.asp?content=Duurzame woningbouw: impact van de technische installatie, 21/03/2011

www.livios.be/nl/_build/_dozz/_build/11206.asp?content=Duurzame woningbouw: milieu-impact en kost van een rijwoning, 28/03/2011

www.livios.be/nl/_build/_newz/_hot/11225.asp?content=Duurzame woningbouw: milieu-impact en kost van een halfopen woning, 5/04/2011

www.livios.be/nl/_build/_newz/_hot/11241.asp?content=Duurzame woningbouw: milieu-impact en kost van een vrijstaande woning, 11/04/2011

www.livios.be/nl/_build/_newz/_hot/11260.asp?content=Duurzame woningbouw: milieu-impact en kost van een appartement, 19/04/2011

ii. CSTC:

- Putzeys K. (2010), Financiële kosten en milieu-impact, WTCB-contact nr. 26, February 2010
- Delem, L. (2010). Methodology for financial and environmental optimization of buildings, extended abstract, ENBRI LCA workshop, June 2010, Lubiljana, Slovenia

b. Co-publications

Peer review

International conference proceedings:

- Spirinckx, C., Vercalsteren, A., Putzeys, K., Allacker, K. and De Troyer, F. (2009). Sustainable building: the search for an integrated method to evaluate the sustainability of different dwelling types, the 6th Australian Conference on LCA, February 18-20 2009, Melbourne, Australia.
- Spirinckx, C., Vercalsteren, A., Geerken, T., Allacker, K. and De Troyer, F. (2009). The SUFIQUAD project – Sustainability, financial and quality evaluation of dwelling types, Lifecycle Management Conference 6-8 September 2009, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa.
- Putzeys, K., Delem, L., Janssen, A., Allacker, K., De Troyer, F., Debacker, W., Spirinckx, C., Vercalsteren, A. and De Nocker, L. (2010). Methodology for optimising the sustainability of buildings. Proceedings of the Euregional Conference Sustainable Building – Towards 0-impact buildings and environments. Maastricht, 11-13 October 2010 (art.nr. 70). Heerlen, The Netherlands: RiBuilT - Research institute BuilT environment of Tomorrow, Zuyd University
- Allacker, K., De Troyer, F., Debacker, W., Spirinckx, C., Vercalsteren, A., De Nocker, L., Putzeys, K., Delem, L. and Janssen, A. (2010). Towards 0-impact buildings: a case-study based analysis. Proceedings of the Euregional Conference Sustainable Building – Towards 0-impact buildings and environments. Maastricht, 11-13 October 2010 (art.nr. 82). Heerlen, The Netherlands: RiBuilT - Research institute BuilT environment of Tomorrow, Zuyd University

- Debacker, W., Allacker, K., Delem, L., Janssen, A., De Troyer, F., Spirinckx, C., Geerken, T. and Van Dessel, J. (2010). An integrated approach for financial and environmental cost optimisation of heating services - Recommendations for a Belgian dwelling case, Proceedings of the ERSCP-EMSU conference, Delft, The Netherlands, October 25-29.

International journals:

- Allacker K. and De Nocker L. (2011). Calculation of the environmental external costs of the Belgian building sector. In: Journal of industrial ecology. (submitted, in reviewing process)

Other

- Poster: De Troyer, F., Allacker, K., Spirinckx, C., Vercalsteren, A., Putzeys, K., Sustainable Building – Search for an integrated method to evaluate the sustainability of dwelling types, ERSCP07, Basel, Switzerland, June 2007, (presentation + poster as result of workshop).
- SuFiQuaD - Sustainability, Financial and Quality evaluation of Dwelling types, PREPARE newsletter, a European network on Preventative Environmental Protection Approaches in Europe, Newsletter 3, pp. 11, July 2008.
- SuFiQuaD - Sustainability, Financial and Quality evaluation of Dwelling types - 'Evaluatie van verschillende woningtypes op gebied van milieu-impact, financiële kost en kwaliteit', vaktijdschrift DIMENSION, September 2008 by FCO MEDIA, Filip Cossement Blvd des Canadiens 118, 7711 Dottignies, Belgium.
- Allacker, K. and Spirinckx, C. (2007). Development of a methodology to optimize dwelling types in Belgium. Extended abstract, Cycle07, Montréal, Canada, October 2007.
- Poster: Allacker, K., De Troyer, F., Debacker, W., Spirinckx, C., Vercalsteren, A., De Nocker, L., Putzeys, K, Delem, L, Janssen, A. Towards 0-impact buildings: a case-study based analysis. Euregional Conference Sustainable Building – Towards 0-impact buildings and environments. Maastricht, 11-13 October 2010, Heerlen, The Netherlands: RiBuilT - Research institute BuilT environment of Tomorrow, Zuyd University.

c. Other activities

- Workshop "Sustainable Building - a search for an integrated method to evaluate the sustainability of dwelling types", organised by K.U.Leuven, VITO and CSTC at the 11th European Roundtable on Sustainable Consumption and Production (ERSCP) in Basel, Switzerland, June 21, 2007.

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8. ANNEXES

ANNEX 1: COPY OF THE PUBLICATIONS

ANNEX 2: MINUTES OF THE FOLLOW-UP COMMITTEE MEETINGS

Annexes are available on our website :
http://www.belspo.be/belspo/ssd/science/pr_transversal_en.stm